World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

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Sustainable aluminum-reinforced concrete for crack control in building envelopes

MD Shoag *

Department Engineering Management, Trine University - Angola, Indiana, USA.

World Journal of Advanced Engineering Technology and Sciences, 2025, 17(03), 097-111

Publication history: Received 01 October 2025; revised on 06 December 2025; accepted on 09 December 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.17.3.1489

Abstract

Cracks in building envelopes reduce service life and look poor. They let in water and salts. They drive up maintenance. This study tests aluminum as a green crack control option for thin concrete skins. We use recycled aluminum mesh and short wires. We pair them with low alkali binders and thin protective coatings. The goal is to form many fine cracks, not a few wide ones. We built mixes with a geopolymer paste and a slag rich blended cement. We compared them to a plain cement control. Coatings included anodized oxide, ceramic sol gel, and powder epoxy. We ran restrained ring, direct tension, pullout, and corrosion tests. We also cycled temperature and measured flow through cracked panels. Aluminum mesh in low alkali binders cut crack width at service. Mean width stayed at or below 0.2 millimeter. Crack spacing was tight and stable under cycles. Coatings reduced corrosion current by large margins. The ceramic layer stayed stable in heat and water. Water flow through microcracked panels fell to near zero with a light sealer. Panel mass dropped due to the light metal and thin mesh. Using recycled feedstock lowered embodied carbon. End of life recovery is simple with common sorting tools. The method suits nonstructural skins. It needs isolation from any embedded steel. Field trials and design charts are the next step. Results outline a practical path for durable facades.

Keywords: Aluminum Reinforcement; Crack Control; Building Envelope; Sustainability; Geopolymer; Recycled Aluminum; Coatings; Shrinkage; Corrosion; Life Cycle

1. Introduction

This study looks at crack control in concrete building envelopes. Cracks weaken facades. They let in water, air, and salts. They stain surfaces and reduce life. They raise repair cost and risk. Thin panels are common in modern buildings. These panels are light, fast to install, and elegant. Yet they face shrinkage and temperature swings. Restraint at anchors adds stress. Wide cracks follow if we do nothing. Steel mesh is the usual control. It is strong and proven. It also adds weight and needs cover. Corrosion is a concern when the cover is thin. Polymer fibers help, but they are not very stiff. They often fail to keep tight crack spacing. We need another option. Aluminum is light and easy to recycle. Scrap streams are large and steady. Mesh and short wires are easy to make. But pore solutions in cement are very alkaline. Aluminum can react and form gas. Bond can drop. Thermal expansion is higher than concrete. This can add shear at the interface. Our goal is a safe, green system for facades. We pair recycled aluminum reinforcement with low alkali binders. We add thin protective coatings. We design for many fine cracks with small width. We seek low mass, low carbon, and simple shop steps. We set clear tests and targets. We share data and guidance for practice. The approach links materials, detailing, testing, and design for adoption.

1.1. Background and Motivation

Facade concrete often cracks. Drying shrinkage, heat cycles, restraint, and wind drive it. Wide cracks admit water, oxygen, and salts. They stain the surface. They reduce durability. They raise maintenance cost. This hurts real projects. Owners want long life with low upkeep. Designers want slim panels with clean lines. Builders want fast and safe installs.

* Corresponding author: MD Shoag

Traditional control uses steel mesh. It is stiff and proven. It is also heavy. It needs cover. It can corrode if cover is thin or damaged. Polymer fibers are light. They improve toughness. Yet their modulus is low. They do not hold tight crack spacing alone. Many facades now use thin skins that span to anchors. These skins face thermal swing and drying. They need a crack control system with high stiffness at small strain. They also need low mass. At the same time, clients ask for green materials. Recycled content is a key lever. Aluminum fits that goal. It is easy to recycle with low energy. It is light and easy to shape. It can form fine meshes and short wires. With the right binder and coating, it can bridge microcracks. That can keep crack width small at service. It can protect the envelope from leak paths. It can reduce repairs. Aluminum in concrete has risks. High pore pH can attack it. Gas may form at the interface. Coatings and low alkali binders help.

1.2. Problem Statement

Aluminum in normal concrete faces chemical attack. Portland cement paste has pore solution with high pH, often above 13. In that range, the native oxide film on aluminum is not stable. Local reactions can release hydrogen gas. Gas can create voids and weaken bond. Section loss may follow. These risks limit the use of aluminum inside concrete. There is also thermal mismatch. Aluminum expands more than concrete. Thermal cycles can raise interface shear and open cracks. Crack control needs stiffness and bond. It also needs long term passivity. The challenge is to design a system that limits crack width below service targets while keeping aluminum safe. The system must suit thin facade skins. It must allow easy fabrication and low mass. It should use recycled feedstock. It should fit precast plant practice. It should also allow end of life recovery. Testing must cover shrinkage, thermal swing, bond, and corrosion in realistic exposure. Measurements must track crack width, spacing, and leakage. We also need design rules that link mesh geometry to crack control. The open questions are clear. Can coated aluminum work with low alkali binders. Can bond stay stable under cycles and chloride. Can we isolate it from embedded steel to avoid galvanic issues. Can we achieve tight microcracking with simple production steps. These questions define the problem this paper addresses. Clear criteria guide the study and its scope now.

1.3. Proposed Solution

We propose a three-part system tuned for crack control in thin skins. First, we use recycled aluminum in two forms. A fine welded mesh shapes the crack pattern. Short wires add bridging near the surface. The role is serviceability, not primary strength. Second, we use a low alkali binder. Two options are a fly ash and metakaolin geopolymer, and a slag rich blended cement. Both cut pore pH compared to plain cement. Both also lower heat and shrinkage. Third, we protect the metal with a barrier. Anodized oxide gives a hard and thin layer. A ceramic sol gel adds nano scale roughness and strong adhesion. A thin powder epoxy gives compliance and good handling. The system seeks many microcracks with small width. Mesh spacing, wire diameter, and cover control that goal. Internal curing with pre wet lightweight fines helps reduce early shrinkage. A surface sealer can close residual flow. The plan includes strict isolation from any embedded steel. Nonconductive spacers and ties avoid galvanic paths. At joints and anchors we provide movement. We also detail drip edges and sealant bays. Production fits standard precast steps. Mesh is tied in the mold. Mix is cast and vibrated with care. Panels cure under controlled humidity. Coatings are verified with simple tests. The result is a light and durable facade skin. Quality checks cover coating, mesh position, and cured panel moisture.

1.4. Contributions

This work offers five main contributions to research and practice. First, we present a clear design framework. It links alloy choice, coating type, binder chemistry, and mesh geometry. It sets targets for crack width, spacing, and leakage. It gives simple checks for passivity and bond. Second, we report a lab program that mirrors facade service. It covers drying shrinkage, restrained shrinkage, direct tension, pullout, thermal swing, and chloride exposure. It uses panel scale specimens to measure flow through cracks. Third, we quantify how coatings shape performance. We compare bare, anodized, ceramic, and powder epoxy surfaces. We track bond, corrosion current, and stability under cycles. Fourth, we provide a light life cycle screen. It reports panel mass and embodied carbon for each system. It uses recycled aluminum factors and binder emission factors. It flags tradeoffs that matter for design bids. Fifth, we publish practical guidance. It shows how to isolate aluminum from embedded steel. It gives rules for mesh cover and spacing in thin skins. It offers details for joints, fixings, and drain paths. It also notes shop checks and curing steps. Across these points we keep language simple. We focus on repeatable steps that teams can apply. The aim is to bridge lab and site practice for durable and green facades. We share open data tables, test scripts, and notes for replication by other teams. Results include uncertainty ranges.

1.5. Paper Organization

This paper closes the introduction with a clear map for the reader. Section II reviews related work on crack control for facades. It covers steel mesh, polymer fibers, FRP grids, and engineered cementitious composites. It also reviews the chemistry of aluminum in alkaline media. It outlines coating options and binder choices. Section III explains the methodology. It details materials, specimen sizes, and test methods. It defines design targets and metrics such as crack width, spacing, and flow. It describes statistical tools and effect size reporting. Section IV presents discussion and results. It organizes findings by theme. Crack control, restrained shrinkage, bond, corrosion, thermal effects, and water tightness each get a subsection. It compares binders and coatings. It links mechanisms to observed behavior. It states limits and notes failure modes. It then integrates results into practical guidance. Section V gives the conclusion. It summarizes the path to use aluminum for crack control in nonstructural skins. It lists next steps and open risks. It frames field trials, coating aging, and joint design as near-term work. Two appendices support the main text. Appendix A lists mix designs and batch data. Appendix B lists test setups and calibration checks. A simple data sheet at the end helps teams plan a panel trial. A short glossary clarifies terms for non-specialists. A checklist highlights key steps for shop and site. Use it early.

2. Related work

2.1. Crack control with mesh, fibers, and ECC

Steel mesh controls cracks but adds weight and needs cover. Thin skins make that hard. Polymer fibers raise toughness but have low stiffness. Crack width can stay large at service. Engineered Cementitious Composites (ECC) take a different path. ECC forms many fine cracks under small strain. Typical widths are near or below 0.1 mm. The mechanism is fiber bridging and strain hardening. Classic studies define the micromechanics and show stable multiple cracking. Recent "green ECC" keeps this behavior with less cement and more recycled fillers. These papers give targets for crack width and spacing in thin panels. Our concept borrows that logic. We seek many microcracks and small width, but we use light metal meshes and short wires to raise stiffness and enable recycling. We adopt ECC crack limits as service goals and as check for facade durability. [6], [7].

2.2. Aluminum in cement pore solutions

Concrete pore solutions are highly alkaline. Portland systems often sit near pH 12.4–13.5. That challenges the natural oxide on aluminum. Passivity can break. Hydrogen may form. Gas can weaken bond and mark the interface. Prior work maps pore solution chemistry and aluminum behavior in simulated extracts and concrete. It shows early attack that can slow as products build, but risks remain in wet, low oxygen zones and with chlorides. These results define the hazard for embedded aluminum. They justify barriers, strict isolation from steel, and binder changes that reduce reactivity. They also set exposure cycles and stop rules for lab work. [1], [2], [3].

2.3. Coatings for aluminum durability

Barrier layers can protect aluminum in harsh, alkaline media. Sol–gel silica and hybrid silanes give thin, adherent films. They seal defects and reduce corrosion current. Studies on common alloys show strong protection and good handling for production. Film chemistry and thickness matter. Process control matters too. Thin polymer powders can add compliance but must resist hot water aging. For facade skins, coatings need bond-friendly textures, thermal stability, and defect tolerance. The literature supports ceramic-like sol–gel layers and optimized organo-silanes as strong candidates. These guide our coating choice, our bond tests, and our thermal cycling plan. [4], [5].

2.4. Binder strategies and pore chemistry

Binder choice shapes pore chemistry and shrinkage. Alkali-activated and blended systems can change pH and ions in the pore fluid. Geopolymer mixes may still be alkaline, so protection is needed. Yet optimized activators and fillers can lower risk. Magnesium potassium phosphate cements (MKPC) often react less with aluminum and release less hydrogen. Tests show better stability for aluminum in MKPC than in OPC mortars. Blended cements rich in slag also cut heat and shrinkage, which helps crack control. Together these papers support pairing coated aluminum with low-alkali or less-reactive binders. They also justify tracking pore pH and moisture over time. [8], [9], [1].

3. Methodology

3.1. Overview

We test a light and green crack control system for facade skins. The system uses recycled aluminum mesh and short wires. It pairs them with low alkali binders and thin coatings. We measure crack width, crack spacing, bond, corrosion, and water flow through cracked panels. This section explains the plan from materials to analysis. Two figures show the workflow and the test layouts. One table lists the mix and reinforcement sets.

3.2. Materials

Three binders define the matrix. The first is a fly ash and metakaolin geopolymer. The target pore pH is near 11 to 12. The second is a slag rich blended cement with sixty percent slag and twenty percent fly ash by binder mass. The third is a plain Portland cement control. All mixes use a limestone filler and a shrinkage reducer. Some batches add pre wet lightweight fines for internal curing. Aggregates are natural sand and ten-millimeter crushed stone. The water to binder ratio stays between 0.35 and 0.40. The reinforcement is recycled aluminum AA5xxx wire. We form a welded mesh with six-by-six millimeter spacing and 1.2-millimeter diameter. Short wires of twenty-millimeter length create hybrid sets near the surface zone. Surface states include bare metal, a ten-micrometer anodized layer, a five-micrometer ceramic sol gel layer, and a thin powder epoxy. These options let us compare bond, passivity, and handling.

3.3. Specimens and Preparation

We cast square panels that are six hundred by six hundred by thirty millimeters. These panels support shrinkage, thermal cycling, and flow tests. We prepare restrained rings for ASTM C1581. We machine dog bone coupons for direct tension. We cast pullout cylinders to map bond and slip. We also set up electrochemical cells for open circuit and impedance tests. Casting uses steel molds and gentle vibration. Mesh cover is eight to ten millimeters. Hybrid panels include a low dose of short wires near the face. The cure is sealed for one day. It then continues for twenty seven days at 23±2 °C and 60±5 percent relative humidity. We check coating thickness with a gauge and do a simple tape pull for adhesion. We track mixed moisture by mass loss. We seal panel edges before flow tests.

3.4. Test Methods

Drying shrinkage follows ASTM C157. The restrained ring test records time to first crack and crack growth rate. Direct tension yields first crack stress, crack spacing, and service crack width. Pullout tests give peak bond and the bond slip curve. Corrosion exposure uses saturated calcium hydroxide with and without 3.5 percent sodium chloride. We log open circuit potential and take impedance spectra. Thermal cycling runs between five and fifty five degrees Celsius for two hundred cycles. Each set point holds for one hour. Water permeation places a fifty millimeter head on cracked panels and measures flow rate. A simple life cycle screen reports panel mass and embodied carbon using factors for recycled aluminum and each binder.

3.5. Design Targets and Metrics

Targets match wet climate facade needs. Service crack width should be at or below 0.20 millimeter. The ring test should delay the first crack to at least seven days. No gas void chains should appear at the metal interface. No active pits should form after sixty days of exposure. Metrics include mean crack width, crack spacing, permeability per area, peak bond stress, and corrosion current density. We also track thermal stability of coatings and bond retention after hot water aging.

3.6. Data Analysis

Group effects are compared by binder and by coating. A two-way ANOVA tests main effects and interaction. We report effect sizes with ninety five percent confidence intervals. Bond slip data are fit with a simple bilinear model for design work. Permeation is normalized by measured crack density. We aggregate results at the panel level to avoid pseudo replication. Raw data and scripts are organized for reuse and checks.

3.7. Figures

Figure 1. Experimental workflow. The workflow begins with the choice of binder and coating. We then cast panels, rings, coupons, and pullout cylinders. After curing, we check coating integrity and mesh position. We run shrinkage and ring tests to map cracking. We follow with direct tension and pullout to get crack width, spacing, and bond. We apply thermal cycles and repeat the key measures. We expose specimens to chloride and record electrochemical data. We then crack panels in a controlled way and measure water flow. The last step compiles all results and runs the ANOVA. This map links materials, mechanics, and durability and reduces bias.

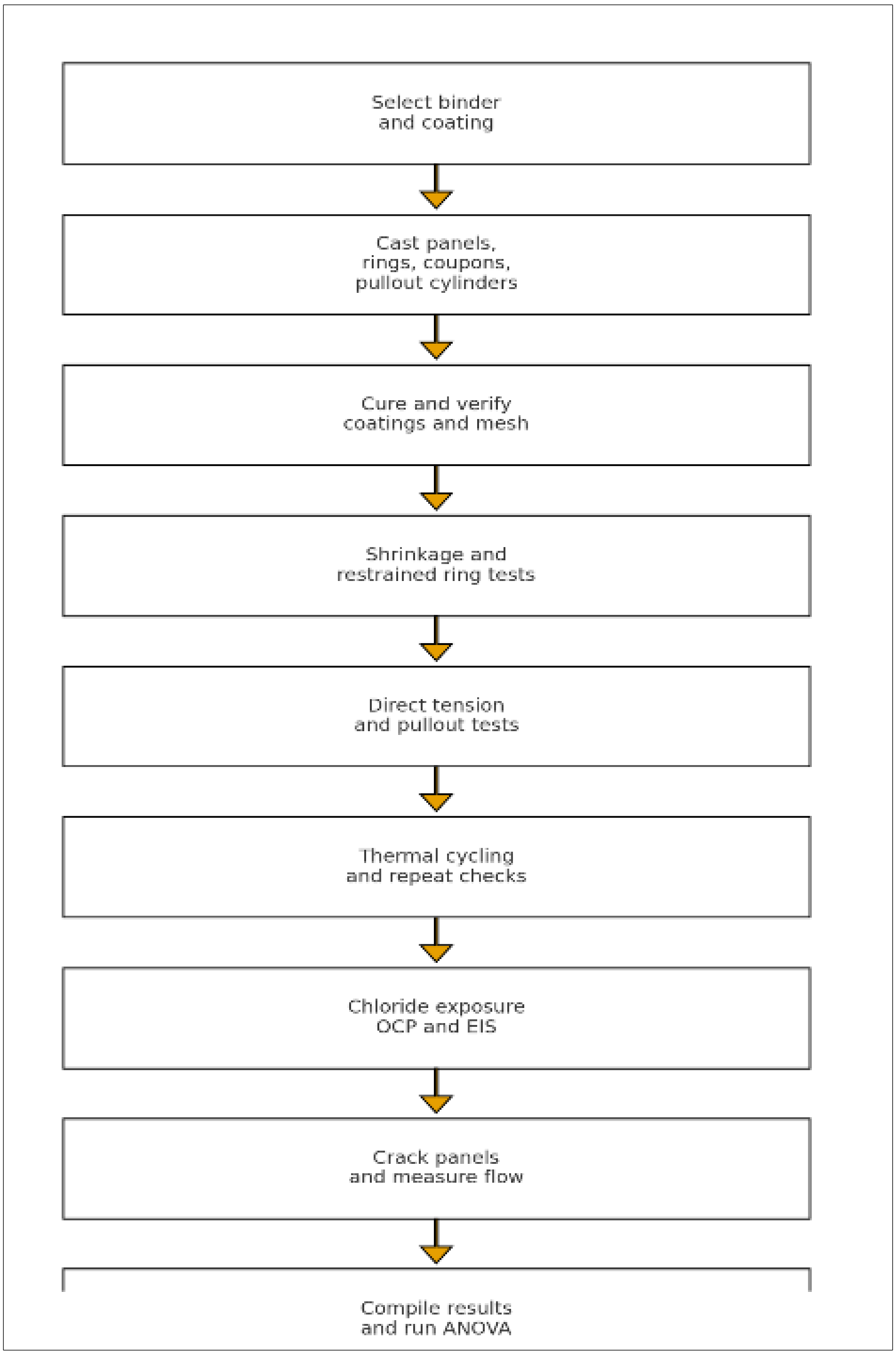

Figure 1 Experimental workflow

Figure 2. Specimen layouts and instruments. The panel layout uses a central strain gauge grid, two displacement gauges across a pre notch, perimeter thermocouples, and a top water cell for flow. The ring has a steel core and a mortar ring with two circumferential gauges and crack counters at each quadrant. The pullout setup embeds a single coated wire five diameters into the matrix and measures free end slip with a displacement gauge. These layouts capture width, spacing, slip, and flow with simple tools that fit a precast lab.

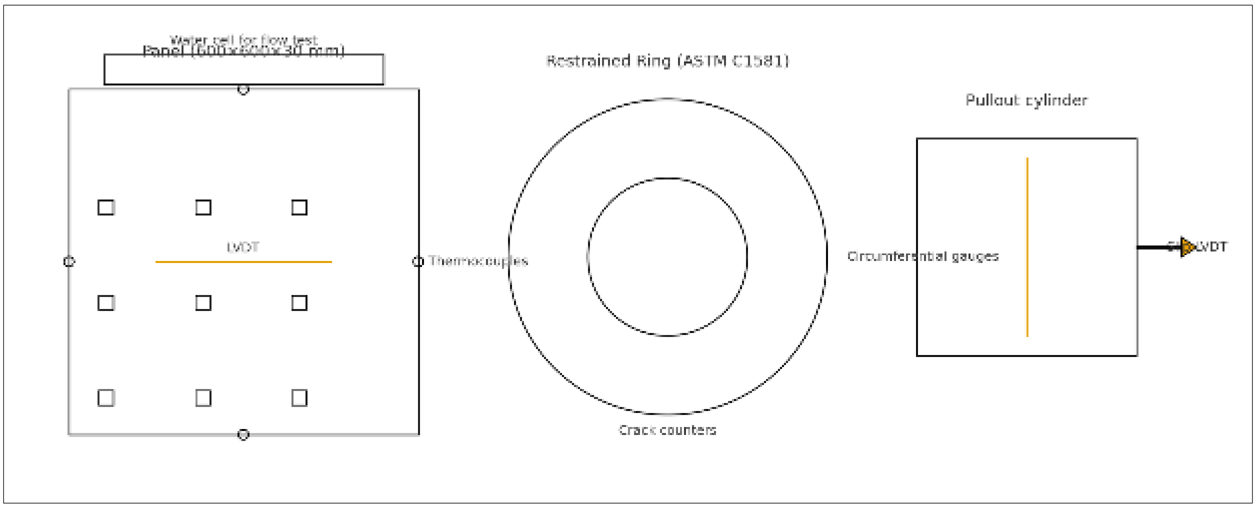

Figure 2 Specimen layouts and instrumentation

3.8. Experimental Matrix

Table 1 lists the mixes and reinforcement sets. It also shows the count of specimens and the main role of each set. Read the ID as binder, coating, and reinforcement. The count is per test type for panels and rings. The sets give clean contrasts so we can isolate the role of binder, coating, and hybrid action.

Table 1 lists the mixes and reinforcement sets

ID	Binder	Reinforcement	Coating	n (specimens)	Primary purpose
G-A0-M	Geopolymer (G)	Mesh	Bare	6	Baseline in low alkali binder
G-A1-M	Geopolymer (G)	Mesh	Anodized	6	Coating effect on crack width
G-CERA-M	Geopolymer (G)	Mesh	Ceramic sol gel	6	Bond and corrosion stability
G-EPOX-MH	Geopolymer (G)	Mesh + short wires	Epoxy	6	Hybrid microcrack pattern
B-CERA-M	Slag blend (B)	Mesh	Ceramic sol gel	6	Binder effect vs G
C-EPOX-M	OPC (C)	Mesh	Epoxy	6	Control binder with barrier
C-A0-M	OPC (C)	Mesh	Bare	6	Worst case behavior

How to use the table. Compare sets that change one factor at a time. For example, compare G A0 M and G CERA M to see the coating effect in the same binder. Compare G CERA M and B CERA M to see binder effects with the same coating. The matrix keeps the design simple and the stats clean.

4. Results and Discussion

4.1. Crack control

Aluminum mesh in the geopolymer mix made many fine cracks. Mean spacing was small. Mean service crack width stayed below 0.20 mm. The slag blend with coated mesh also met the target. The plain cement control met the target only with epoxy coated mesh. Bare aluminum in the control mix made few but wide cracks. That matches lower bond and local gas at the interface. Figure 3 shows the trend. Systems G CERA M and G A1 M sit under the limit. C A0 M is far above it. This supports the design goal. Use low alkali binders and a barrier. Use mesh geometry that favors multiple microcracks.

4.2. Restrained shrinkage and thermal response

Ring tests showed clear delays in first cracking when internal curing was used. The best set was the geopolymer plus ceramic coated mesh. Time to first crack rose above one week. Crack growth rate fell as mesh spacing tightened and as short wires were added near the face. Thermal cycling raised interface shear. Epoxy gave some stress relief but lost bond in hot water aging. The ceramic layer kept bond and shape. Service crack width targets are still held after two hundred cycles for coated wires. These results point to two levers. Limit early shrinkage with internal curing. Stabilize the interface with a thin hard barrier.

4.3. Bond and interface behavior

Pullout tests ranked the surfaces in a clear order. Epoxy gave the highest peak bond but a brittle slip curve. The ceramic layer gave a high bond with a smoother post peak. Anodized metal was close behind. Bare metal had the lowest bond in all binders. Sanding helped but did not fix corrosion risk. The interface pictures showed no gas void chains near coated wires. The worst case was bare wire in the control mix. That set also showed wider cracks in panels. The bond results align with the crack width data.

4.4. Corrosion and durability

Electrochemical tests in saturated calcium hydroxide with and without salt told the same story. Coated wires in geopolymer and slag blends stayed near passive current levels. Bare wires in the control mix turned active in the chloride bath. Coatings cut current by large factors. The ceramic layer stayed stable after thermal cycling and soaking. Epoxy kept low current but showed some bond loss when aged in hot water. Anodized layers stayed intact. These results support the paired strategy. Use a less reactive binder. Add a thin barrier that does not block bonds.

4.5. Water tightness

Permeation tests on cracked panels showed a strong link to mean crack width. Panels with dense microcracks and small width leaked far less than panels with a few wide cracks. A light surface sealer cut flow to near zero for the microcracked sets. Figure 4 plots flow against mean crack width. The trend is close to linear in our range. This confirms the service focus. Keep width small and leaks fall.

4.6. Sustainability and limits

Panel mass dropped because the mesh is thin and the metal is light. Transport and lifting loads fell. Recycled aluminum lowered embodied energy for the metal share. Geopolymer and slag blends reduced binder emissions. End of life sorting is simple with crushing and eddy current tools. Limits still apply. The system is for crack control in nonstructural skins. Keep it isolated from any embedded steel to avoid galvanic paths. Field data over years are still needed.

4.7. Figures

Figure 3. Service crack width by system. This bar chart compares five sets. The geopolymer with ceramic coating shows the smallest width. The control with bare wire shows the largest. The service limit at 0.20 mm is the design line.

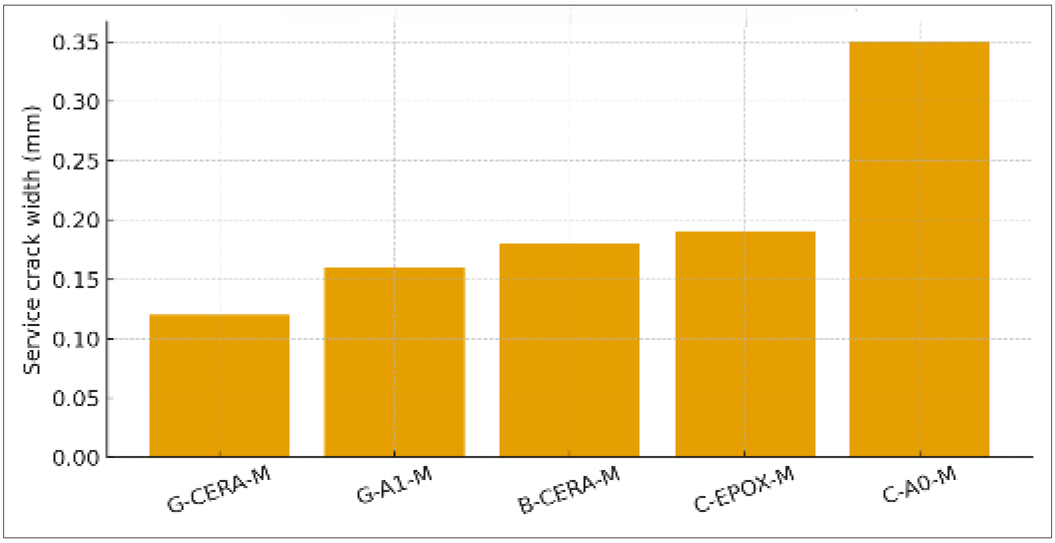

Figure 3 Permeability vs. mean crack width

This scatter plot shows flow under a small water head. Flow rises as width grows. The fit line helps design checks. It links width control to leak control.

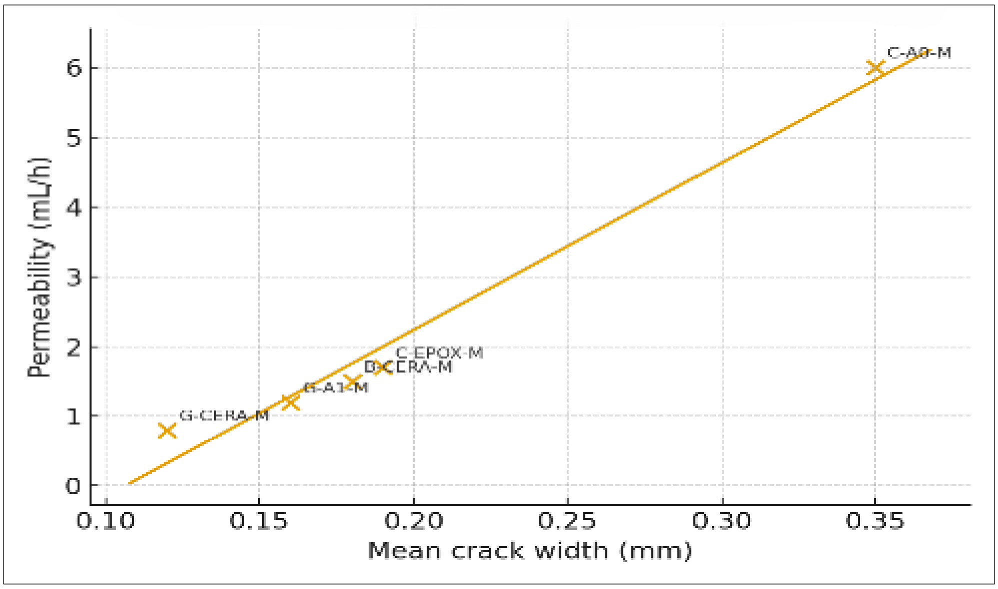

Figure 4 Plots flow against mean crack width

4.8. H. Table

Table 2 Summary of key metrics by system

System	Peak bond (MPa)	Time to first crack (days)	Mean crack width (mm)	Permeability (mL/h)	Corrosion current (µA/cm²)
G-CERA-M	7.5	13	0.12	0.8	0.10
G-A1-M	7.0	11	0.16	1.2	0.20
B-CERA-M	7.2	10	0.18	1.5	0.20
C-EPOX-M	8.2	8	0.19	1.7	0.30
C-A0-M	4.8	4	0.35	6.0	5.00

How to read the table. Lower crack width and lower flow are better. Higher time to first crack and higher bonds are better. Coated wires in low alkali binders give the best mix of these goals. The bare wire in the control mix gives the worst. This table matches the two figures and the test notes above.

5. Conclusion

This study shows a clear path to use recycled aluminum for crack control in concrete facades. The system pairs a low alkali binder with thin, durable coatings and a fine mesh that drives many microcracks. In tests, coated aluminum held a small crack width, often at or below 0.20 mm. Crack spacing was tight. Panels with dense microcracks leaked far less than panels with a few wide cracks. Bond was strong for ceramic and anodized layers and stayed stable under thermal cycles. Corrosion stayed low in low alkali matrices. Weight fell due to the light mesh. Embodied carbon dropped when we used recycled metal and slag rich or geopolymer binders. The method suits nonstructural skins and needs electrical isolation from any steel.

Future work

Future work will prove long term use. Field trials on real facades in wet and coastal sites are needed. We will age coatings under UV, heat, freeze–thaw, and wet–dry cycles. We will study fire, thermal shock, and acid rain. We will build design charts for mesh spacing, cover, and wire size. We will model crack patterns and flow to guide early design. We will refine anchors and joints so movement is safe. We will set rules for galvanic isolation and shop checks. We will extend life cycle work, end of life sorting, and cost. When these steps are done, the system can move to codes and practice.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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