Mesh reinforcement in masonry mortar coatings: a systematic literature review

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Abstract

Mortar coatings have a major influence on a building's aesthetics, valorization, and habitability, with significant effects on the mechanical behavior of masonry walls. Multiple types of meshes can be embedded in plaster to enhance both masonry and coating's mechanical behavior, restrain crack formation, enhance the bonding between layers, and increase the wall's seismic resistance. The reinforcement technique has simple execution and is suitable for many applications, including the strengthening of non-load bearing walls, façade performance improvement, and restoration of historical buildings. However, there is an absence of guidelines and specifications for design and execution, resulting in high variability in field applications due to the many variables involved and few in-depth studies. This paper presents a systematic review of the effects of mesh reinforcement in cementitious mortar coatings and its major applications. Mortar and mesh parameters and influences, the status of analytical and simulation models, and suggestions for future research are described.

Keywords: coating, reinforced, façade, cracking, composite.

INTRODUCTION

Masonry elements are susceptible to the occurrence of several pathological manifestations that reduce the building's overall performance and durability due to its nature, composed of multiple layers of different materials, and exposition to multiple deterioration agents. There is also the influence of design specifications, construction techniques, quality control, and, sometimes, a lack of specific building codes [1, 2]. Such a scenario raises concerns about building safety, especially for historic buildings [3]. Coatings have major relevance to a construction's performance, influencing the aesthetics, security, comfort, and valorization of buildings. This system characterizes the external visual, customizes the inner rooms, regulates waterproofing, thermic and acoustic insulation, fire safety, and many other factors involved in maintainability and usage [4, 5]. Mortar coatings also enhance the mechanical behavior of masonries by slenderness reduction, cross-section increase, and stress distribution [6, 7]. Masonry performance can be improved even more if reinforcing meshes are embedded in the coating layer, a technique known for its low cost, ease of execution, and high compatibility with multiple materials [8-10]. This procedure provides greater mechanical strength for masonries under multiple load conditions and many studies suggest it is suitable for repair, retrofitting, and reinforcement applications, as well as seismic strengthening of non-structural infill walls [7, 11-13].

Cementitious mortars are known for their high rigidity, showing little or no plastic deformation. Hence, the coatings suffer from the occurrence of cracking when subjected to tensile stresses, caused by various phenomena, and the use of reinforcing elements can provide more than just higher tensile strength. Visible cracking results from the propagation of microcracks along paths of lower resistance in the cementitious microstructure, and the mesh wires act as resisting cores since more energy is needed to pass through its surroundings, restraining the opening and propagation of cracking [14, 15]. Also, the reinforcement distributes stresses along the mortar layer [14, 16-19], and may be used to enhance the bonding with the masonry or between multiple layers to reduce the risk of coating spalling and falling due to the high specific surfaces of the meshes [20]. Microstructural understanding of the reinforcements is also very important, since the mortar's rheology and reinforcement's geometrical features, as well as the chemical compatibility between them, are strongly connected to the bonding and behavior of the composite [21]. A good interlocking combination between mortar and reinforcement is known to provide great results in retrofitting applications, being able to enhance the energy absorption, displacement, and load capacity of wallets by more than 100% [22]. The technique is described in some international standards, albeit in an incipient way [20, 21, 23]. The Brazilian Standards (NBR), for example, recommends the use of metallic mesh reinforcement to avoid cracking in transition zones between different materials subjected to differential deformation and as support for thick coating layers [24-26]. However, the normative prescriptions

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are superficial and very limited. There is also an absence of guidelines and specifications for the design and execution of such procedures, resulting in high variability in real applications and endorsing the need for in-depth studies about efficiency, methodology, and performance [20, 22]. Also, the development of analytical and simulation models for reinforcement design is hampered due to the intrinsic heterogeneity of such materials and the numerous amount of variables that affect its behavior, such as mesh's material, wire diameter, durability, grid format and spacing, mortar's type and mechanical properties, the use of connectors, type of masonry, and loading conditions [20, 27].

The potential benefits of coating reinforcements, added to the increasing need for an upgrade of existing buildings due to deterioration, deficient maintenance, and the need for compliance with new performance standards, have inspired more in-depth research on the topic [28-30]. Mesh reinforcements are suitable for strengthening and repair of structural, historical, and non-structural masonries. However, the high number of influent factors and test procedures hinders a clear understanding of the technique's state of development, specifications, and potential applications. The main goal of the present systematic review is to present a wider understanding of the reinforcement of masonry cementitious mortar coating with these elements, observing how the mesh, masonry, and mortar properties affect the system performance under different applications. Such understanding is fundamental to the development of further studies focused on the optimization of the technique and examination of the microstructural relationship between mesh and mortar matrices aspiring for enhanced performance of mortar coatings. Along these lines, this review used a variant of the 'population, phenomena of interest and context' (PICo) framework [28] as a guide to establishing the following research question: what are the effects of mesh reinforcement in cementitious mortar coatings?

METHODOLOGY

The standards of the 'preferred reporting items for systematic review and meta-analysis' (PRISMA) [31] were adopted as guides for this systematic review. The study is divided into three main steps shown in Fig. 1 and further explained: 1) identification and collection of potentially relevant studies; 2) screening, assessment, and filtering accordingly to inclusion and exclusion criteria; and 3) information gathering, analysis, and synthesis. Automated searches were performed on SCOPUS, Web of Science, SciELO, and Engineering Village databases along with a manual search on Google Scholar for increased coverage. The automated search filters included journals, conference, and review papers, along with book chapters, without further restrictions such as publication year. The Google Scholar query included doctoral dissertations due to the database's coverage. The keywords, strings used, number of returned results, and those available to full-text access in each database are presented in Table I. The number of documents from the manual search in Google Scholar represents those whose titles were related to the research question and so were retrieved. The screening process consisted of duplicates removal (using the Mendeley Desktop software) and application of the following exclusion criteria during abstract analysis, followed by full-text reading: 1) meshes not used in cementitious mortar layer; 2) studies focused on the analysis of other materials (e.g. cement substitution); 3) concrete reinforcement techniques (e.g. carbon fiber reinforced polymers); and 4) parts of wider studies already included in the final sample.

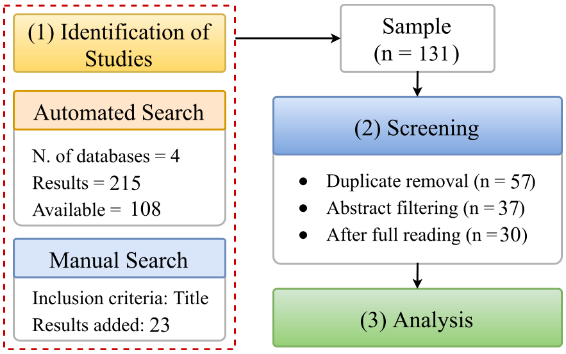

Figure 1: Flow diagram of the review steps.

The data collection occurred through the full reading

Table I - Search databases, strings, and the number of results for automated and manual search.

Database	String	Returned results	Available results
Engineering Village	(mortar OR plaster) AND (mesh) AND (coat*)	78	30
SciELO	[(mortar) OR (plaster)] AND (mesh) AND (coat*)	3	3
Scopus	TITLE-ABS-KEY [("mortar" OR "plaster") AND ("mesh") AND ("coat*")]	82	40
Web of Science	ALL=[(mortar OR plaster) AND mesh AND coat*]	52	35
Google Scholar	Allintitle: mortar mesh coating; mortar mesh reinforcement; plaster mesh coating; plaster mesh reinforcement; mortar mesh reinforced; plaster mesh reinforced		23
Total		215	131

of the texts and sought information regarding geometrical and material characteristics of mortars and meshes, type of masonry and analysis (experimental, analytical, or simulation), experimental design, and resulting mechanical behavior from the mesh incorporation (e.g. changes in tensile strength, cracking behavior, failure modes, etc.). The data were grouped according to the proposed system application (e.g. façade cracking, masonry strengthening, etc.). Publication year, origin country, and type of publication (e.g. journal, conference paper) were collected to perform a quantitative analysis of the results. Authors' comments were also observed to construct an overview of the body of knowledge involving meshes in mortar layers. Network maps of keywords and co-authorship relations from the final sample documents were drawn using the VOSviewer software [32]. For the keyword map, 'author keywords' were selected and filtered for synonyms and variations of form, resulting in 88 keywords. In the co-authorship map, the author's circle size used the number of occurrences as a proportion, grouped by origin country manually.

RESULTS

The search was conducted on Feb 11, 2022. The starting sample of 131 documents was reduced to 37 after duplicate removal and abstract screening. From these, seven were removed after full-text reading because they were not related to the research proposal. The removed documents and the reasons for their elimination are detailed in Table II. The final sample for analysis consisted of 30 documents, detailed in Table III. In this review, the different kinds of stones used for masonry building (e.g. cobblestone, sandstone) were considered simply as 'stone' while the varied kinds of bricks were discriminated. Likewise, applications were grouped according to their main purposes such as: composite design, reinforcement of façade coatings (against cracking and detachment), masonry strengthening (load bearing and rehabilitation), and seismic strengthening and retrofitting, illustrated in Fig. 2. The design of composite elements for structural repair or design of load-bearing elements, as well as concerns about the durability of the composite, constitutes a wider area of knowledge and are beyond this review's scope. For more information in such scenarios, the authors recommend consulting specific publications and reviews [38-41]. The strengthening and retrofitting documents were grouped together for discussion due to similarities in tests and analysis.

The network of keywords, presented in Fig. 3, highlights masonry as the most occurring keyword, with strengthening, mortar, composite, retrofit, reinforced mortar, seismic, and coating also appearing intensively. This indicated the most common uses of mesh reinforcements in mortar layers. The keyword mesh is scattered among others that indicated the type of reinforcement, showing a high variability for the kind of material employed in such applications. The co-authorship map (Fig. 4) revealed that most of the documents analyzed were from Italy. These documents were centered on masonry strengthening with an emphasis on the seismic performance of wall frames. A common theme explored in other European documents is motivated by building guidelines concerning safety under seismic activity [13], especially in the case of older masonry structures with architectural heritage [16, 42]. The second country with more documents was Brazil, with research spread among individual groups, with one or two publications each, including one document in association with Portuguese authors. Most of the documents were associated with the effects of mesh reinforcements in building façades, while three focused on masonry strengthening, and one on reinforced mortar plates, a type of composite. The documents from Egypt, Singapore, and Saudi Arabia examined the mechanical behavior of composite plates with different kinds of meshes. Fig. 5 summarizes the number of documents per application, exhibiting a major debate in the literature over strengthening applications. The use of meshes in façade coating appears next, with relatively new studies (the oldest document dates from 2015), followed by composite and retrofitting. The strengthening and retrofitting documents are discussed together, as they are very similar and, in some cases, complementary. Is worth noting that composite applications other than coatings are vast and not the focus of this review, so the findings described in the following sections consider the results of composite specimens as an analysis of individual coating layers.

Table II - Excluded documents after full reading and reasons.

Type[0]	Reason for removal	Ref.
JP	Numerical study on the structural behavior of masonry vaults under seismic activity	[33]
JP	Finite element analysis of chimneys' structural behavior under seismic activity	[18]
JP	Study focused on analysis of insulation materials	[34]
JP	Study focused on the evaluation of insulation plaster	[35]
CP	Part of a wider study already included	[36]
JP	Reinforcement in horizontal joints, not coating	[37]
JP	Method for concrete structure reinforcement	[29]

[0]: *CP: conference paper; JP: journal paper.*

Table III - Included studies and main characteristics.

Type[0]	Country	Application	Mesh material	Mesh opening (diameter) (mm)[1]	Masonry[2]	Analysis[3]	Face[4]	Coating thickness (mesh position) (mm) [5]	Ref.
JP	Saudi Arabia	Composite	Woven galvanized steel	3.15x3.15 (0.63); 6.3x6.3 (0.63); 12x12 (0.63)	NA	EX	NA	12.5 (-)	[14]
CP	Brazil	Composite	Polymer (rhomboid); metallic (3 types)	-	NA	EX	NA	20 (10)	[43]
JP	Singapore	Composite	Bamboo fiber	10x10 (-); 15x15 (-); 20x20 (-)	NA	EX	NA	19 (-)	[44]
JP	Spain	Composite	Epoxy coated vegetal fiber	24x8 (var.)	NA	EX, AN	NA	10 (5)	[19]
JP	Brazil	Façade coating	Galvanized steel[A]	25x25 (1.24); 1/2”, 1” (0.56); 1” (0.18); 2” (1.24)	NA	EX	NA	50 (33)	[21]
CP	Brazil	Façade coating	Electrowelded steel wire; alkali-resistant fiberglass; polymer (rhomboid)	25x25 (-); 10x10 (-); 20 (-)	NA	EX, AN	2	35 (17.5)	[20]
JP	Brazil	Façade coating	Electrowelded galvanized steel; steel (hexagonal); high-density polyethylene	25x25 (1.24); 12.7x12.7 (0.56); 13 (0.4)	HB	EX	1	25 (10); 50 (30)	[27]
JP	Brazil	Façade coating	Electrowelded galvanized steel; steel (hexagonal); high-density polyethylene	25x25 (1.24); 25.4x25.4 (0.71); 13 (0.4)	NA	EX	NA	50 (15); 50 (25); 50 (30)	[17]
CP	Brazil	Façade coating	Electrowelded galvanized steel	25x25 (1.24)	NA	EX	NA	50 (var.)	[15]
JP	Portugal, Brazil	Masonry strengthening	Welded steel bars	100x100 (4.2)	HB	EX	2	30 (15)	[6]
JP	Italy	Masonry strengthening	Alkali-resistant fiberglass-A; unidirectional steel strip-B	A-23x23 (2.13); A-40x40 (1.25); B-4.25 (warp)	SB	EX, SM	2	12-30 (-)	[45]
CP	Italy, United Kingdom	Masonry strengthening	Alkali-resistant fiberglass	30x35 (-); 50x50 (-)	SB, ST	EX, SM	1, 2	20-30 (-)	[30]
JP	Italy	Masonry strengthening	Alkali-resistant fiberglass	66x66 (2.19; 3.11)	SB, ST	EX	2	30 (0)	[46]
JP	Italy	Masonry strengthening	Alkali-resistant fiberglass	33x33 (3.8); 66x66 (3.8); 99x99 (3.8)	SB	EX	1	30 (0)	[3]
JP	Italy	Masonry strengthening	Alkali-resistant fiberglass	66x66 (3.8)	SB, ST	EX, SM	2	30 (15)	[16]
JP	Italy	Masonry strengthening	Alkali-resistant fiberglass-A; steel-B	A-33x33 (-); A-66x66 (-); A-99x99 (-); B-150x150 (5.0); B-200x200 (6.0)	SB	EX	2	30 (0)	[47]

(to be continued)

Type[0]	Country	Application	Mesh material	Mesh opening (diameter) (mm)[1]	Masonry[2]	Analysis[3]	Face[4]	Coating thickness (mesh position) (mm) [5]	Ref.
DT	Brazil	Masonry strengthening	Welded steel bar	10x10 (5.0)	HB	EX	2	20-50 (0)	[48]
JP	Brazil	Masonry strengthening	Electrowelded steel wire	50x50 (2.77)	SB	EX, SM, AN	NA	20 (0)	[11]
JP	Italy	Retrofitting	Electrowelded steel wire; hot-rolled ribbed steel	50x50 (2); 200x200 (6)	HB	EX	2	25 (12.5)	[42]
JP	Iran, Australia	Retrofitting	Steel (hexagonal); polymer; alkali-resistant fiberglass	20 (-); 6x6, 15x15 (-); 6x6 (-)	SB	EX	2	20 (0)	[22]
JP	Iran	Retrofitting	Crimped steel wire	- (3.0)	SB	EX	1	30 (0)	[10]
JP	Italy	Seismic strengthening	Alkali-resistant fiberglass	5x5.9 (-)	HB	EX, SM	1	20 (0)	[12]
JP	Italy	Seismic strengthening	Alkali-resistant fiberglass	5x5.9 (-)	HB	EX	1	20 (0)	[49]
JP	Italy	Seismic strengthening	Alkali-resistant fiberglass; stainless steel cord	66x66 (3.56)	ST	EX, SM	1, 2	30 (0)	[50]
JP	Italy	Seismic strengthening	Alkali-resistant fiberglass	66x66 (3.46)	SB	EX	1	30 (0)	[51]
JP	Lebanon, Spain	Seismic strengthening	Bitumen coated fiberglass; basalt fibers; steel wire	25x25 (-); 25x25 (-); 13x13 (0.5)	HB, SB, ST	EX	1, 2	8 (5)	[13]
JP	Turkey	Seismic strengthening	Square galvanized steel	25.4x25.4 (1.5)	HB	EX	2	25 (5)	[7]
JP	Turkey	Seismic strengthening	Square steel	16x16 (1.1)	HB	EX	1	15-30 (0)	[52]
JP	Turkey	Seismic strengthening	Square steel	16x16 (1.1)	HB	EX	1	15-30 (0)	[23]
JP	China, USA	Seismic strengthening	Polypropylene	50x50 (8)	SB	EX	NA	10 (-)	[9]

[0]: CP: conference paper; JP: journal paper; DT: Doctoral thesis; [1]: (-) missing information; (var.) variable data; [2]: masonry type: HB: hollow brick; SB: solid brick; ST: stone; NA: not applicable; [3]: AN: analytical; EX: experimental; SM: simulation; [4]: number of coated faces, if applicable; [5]: total thickness of mortar layer and mesh distance from the base; [A]: varied types of metal mesh (square, hexagonal and rhomboid).

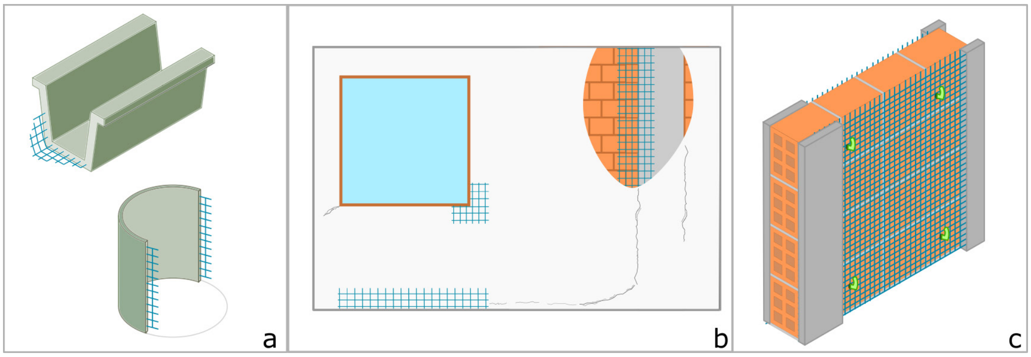

Figure 2: Illustrations of mesh uses in composite design (a), façade coating reinforcement for cracking control (b), and masonry strengthening for load-bearing scenarios (c).

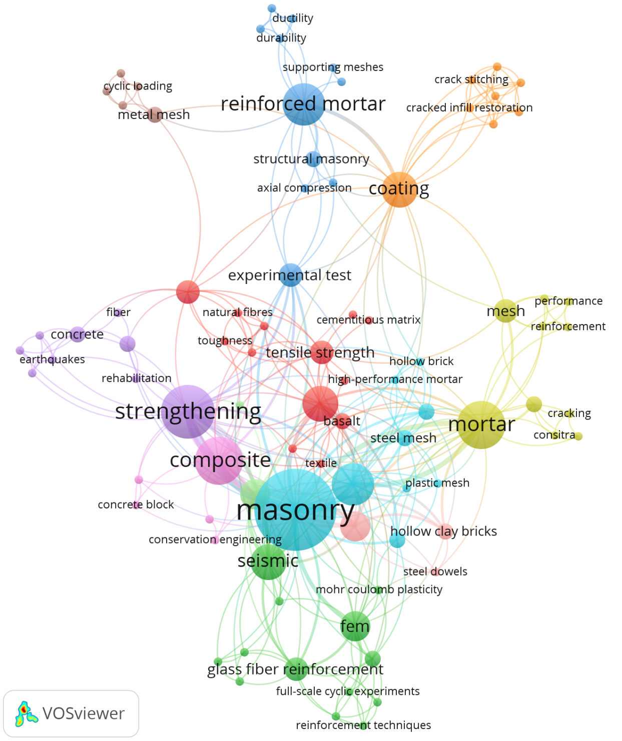

Figure 3: VOSviewer of co-occurrence by keywords map.

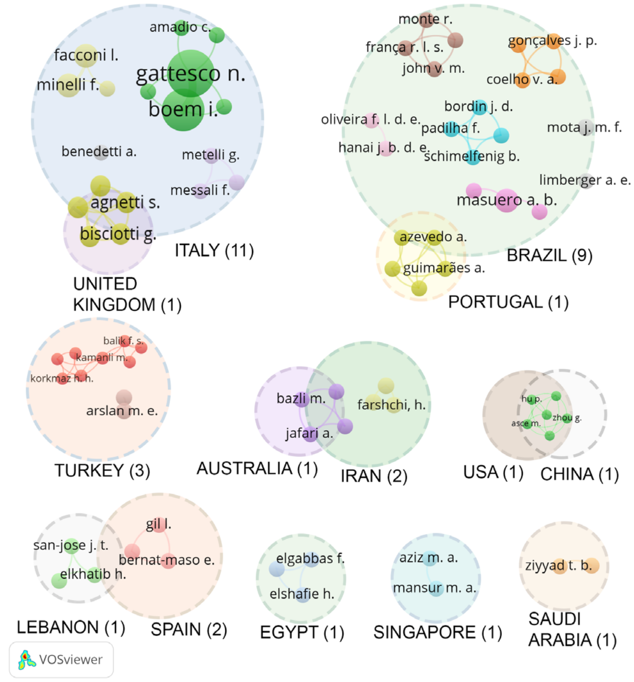

Figure 4: VOSviewer of co-authorship by authors map manually grouped by country.

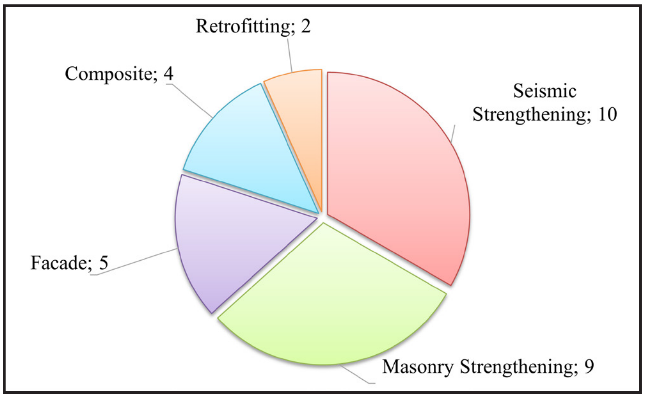

Figure 5: Number of documents per application.

Composites

A ferrocement element is composed of a combination of Portland cement mortar with a reinforcement mesh layer, somewhat similar to reinforced concrete but with a much smaller thickness (usually around 25 mm). Usually, the meshes are metallic, but there are no restrictions for the material used, such as plastic, fabric, glass, basalt, and other alkali-resistant fibers [14, 40]. By this definition, the materials described as composites in the documents analyzed, composed of mesh-reinforced mortar plates, are individual cases of ferrocement, also known as the fabric-reinforced cementitious matrix (FRCM) or reinforced mortars [19, 43]. All documents presented only experimental analysis, except for [19], which also proposed adjustments for an analytical model describing the tensile behavior of FRCM with three stages of deformation.

Reinforcement design: four of the five analyzed studies used high compressive strength mortar (39 to 75 MPa). The plates' thickness varied between 10 and 40 mm, meshes opening from 3.15x3.15 mm to 24x8 mm, and mesh wire diameter between 0.5 and 2.5 mm. The elastic modulus of vegetal fiber reinforcements varied between 4.87 and 38.74 GPa (after resin coating, if used) and ultimate stress between 91.9 and 630 MPa. Steel wire meshes presented 200 GPa for elastic modulus and 350 MPa for ultimate stress. No study that tested multiple materials (vegetal, metal, and polymer) presented full mesh characterization for comparison.

Mechanical behavior: the consulted studies showed good behavior of composites with steel and vegetal meshes, considering each particularity and treatment for synergy with the cementitious matrix. Steel meshes are often preferred, but some vegetal alternatives indicate benefits through low cost, lower densities, and sustainability concerns. Mansur and Aziz [44] investigated bamboo fiber mesh reinforcement and mentioned important aspects of the use of vegetal meshes in cementitious matrices such as fiber treatment with sealants to reduce water absorption and shrinkage. Fiber degradation within the matrix can be avoided with the use of resin coatings that also contributes to bond strength and stiffness. Better results of bonding strength were found with epoxy coating in comparison with polyester [19]. One or two layers of bamboo or hemp mesh promoted higher ultimate tensile strength compared to non-reinforced mortar specimens (19.3% to 275%). Flax, sisal, and cotton mesh reduced the property between 5% and 39%, even with epoxy coating [19, 44]. In general, smaller mesh openings produced the highest flexural strength [44]. Bavastri and Limberger [43] observed increments in ultimate flexural strength between 3.47% and 13.1% using small opening sizes, while a wider grid provided a negligible 0.35% increase (the opening values were not supplied). This effect was likely due to the higher number of wires in the composite, as suggested by the findings of Shannag and Ziyyad [14], where the difference between small and medium grids (3.15 and 6.3 mm steel square mesh) become almost negligible with four layers. The same study found at least the double peak strength when using four instead of two layers. The wider grid used by Bavastri and Limberger [43] was a weaved hexagonal steel mesh, known as a 'chicken net', and its negligible influence could be associated with its great deformability and variation in strength between the orthogonal directions.

Cracking, deformation, and microstructure: regarding cracking, higher energy absorptions were associated with smaller grids, better matrix-reinforcement interaction, and higher stiffness of the meshes. Those composites with low elastic modulus mesh (cotton, bamboo, and weaved steel) produced wider cracking at ultimate strength, presented higher deformations, and even reduced the cracking stress needed for the first crack to appear [14, 19, 43, 44]. Mansur and Aziz [44] observed higher cracking strength with an increase in casting pressure and with the use of a water sealant in bamboo meshes, as such treatments reduced the swelling and shrinking of fibers inside the matrix due to early water absorption, a major problem related to the use of vegetal fibers that compromises the surface interaction and bonding between mesh and mortar. Also, surface treatments may affect the mechanical properties of the fibers, where the fluidity and ability of the resin to penetrate the internal structure of the yarns must be analyzed and controlled [19]. Failure by mesh rupture was observed for steel, polymer, hemp, flax, and cotton (wire diameter between 0.5 and 1.5 mm), indicating good bonding between matrix and reinforcement. Differently, bamboo and sisal showed failure by mortar slip, associated with weaker bonding and possibly the higher diameter (2.5 mm) of the sisal fibers [14, 19, 43]. Such findings suggest that, although the tensile behavior is strongly influenced by the number of fibers and the failure mode becomes gradually more ductile, spalling and detachment of the mortar cover is possible at high reinforcement ratios [14, 19]. Shamseldein et al. [29] observed a tensile strength growing tendency of mortars reinforced with basalt fibers as more layers were added and more resistant elements became part of the material cross-section. However, there seems to be a limit to be defined beyond which delamination starts to occur depending on the mesh properties. The use of fiber-added mortars may be impaired since longer fibers prevent the mortar flow through the mesh, leading to imperfections and poor bonding. Most authors did not evaluate the influence of reinforcements on the mortar absorption properties. However, Bavastri and Limberger [43] reported a reduction in the capillary absorption of mortars using metallic meshes with small openings. This effect should be studied more since the property influences the durability of the coating.

Façade coating

The use of meshes in façade coatings is supported by the recurrent occurrence of pathological manifestations and the importance of the system for building design, quality, and performance [2, 4, 5]. The mortar coatings are susceptible to differential deformations as they are composed of juxtaposed layers with different properties. The resulting stress state often causes fractures, cracking, and detachments [21]. Reinforcement meshes are applied in various situations, especially corners of openings and transition zones between different materials, acting as distributors of punctual stresses and giving ductility to the coating, reducing the large cracking to smaller, distributed, and sometimes harmless, microcracks [17, 27]. Only one study [20] presented an analytical model for the determination of the coating stress state, considering the occurrence of cracking in the structure under the coating. The others performed experimental analysis under flexural, impact, and thermal loadings in test specimens and panels.

Reinforcement design: the main types of meshes used in façade reinforcement are electrowelded metallic with a square opening (EMS), weaved metallic with a hexagonal opening (WMH), expanded metal with a diamond opening (EMD), polymer meshes with various openings, and alkali-resistant fiberglass with a square opening (AFG). The WMH and EMD were initially produced for animal fencing or light applications, where the free passage of light and air is desired (e.g. guardrails and doors). They are highly deformable, and this may compromise their performance in mortar coatings in comparison to others. The EMS has opposite characteristics, being structurally strong with good uniformity in spacing and diameter, but harder to handle [21]. Five studies verified the EMS since it is the one recommended by the Brazilian standard NBR 13755 [24]. The mesh openings varied from 2x2 to 25x25 mm, with diameters from 0.18 to 1.65 mm [21]. The EMS with 1.24 mm wire and 25x25 mm opening presented the highest tensile strength, an order of magnitude higher than the polymer meshes, with reported wire strength between 400 and 600 MPa. The studied WMH presented a sensible gain of strength with smaller mesh openings and wire diameter due to the higher number of wires in a same-size specimen [17, 21, 27]. AFG meshes were close in strength to EMS, although they had smaller openings.

The mortars utilized had flexural strength varying from 0.61 to 2.79 MPa, with a reported elastic modulus of 7.58 GPa [20, 21]. Mortar strength seems to significantly affect reinforcement behavior [27]. Some authors [21] suggest that the closer the elastic moduli between mesh and mortar, the better the interaction between both. Others [17], however, argue that the proximity between matrix and reinforcement can be a problem since the mesh won't be able to increase the mortar resistance to deformation, as seen from the contrary behavior found between EMS and polymer meshes. Although mortar thickness exerts a significant influence on the performance of façades, especially regarding safety, adherence, and cracking behavior, there was no discussion regarding the property. Most studies tested with 50 mm, yet none explained why this size was adopted. A possible reference is the Brazilian standard NBR 13755 [24], which establishes limits for the thickness of a single coating layer between 20 and 50 mm. Only two documents tested with a smaller thickness, but the difference between materials and test conditions is such that any comparison is hindered. The major mesh position was in 2/3 of the layer from the base, followed by the middle of the layer [20, 21, 27]. Some authors [17] found more contribution for flexural strength using the mesh in the external part of the layer, while others [15] found no significant variation along the height.

Mechanical behavior: mortars reinforced with WMH or polymer meshes presented the same or lower performance compared to unreinforced specimens. This effect is associated with their higher deformability, relative lower resistance, and possible geometric incompatibilities, also explained as lower bonding due to the mesh format when the mesh strength, material, and wire diameter were the same as EMS [17, 21]. The studies that compared different meshes suggested higher performance of the EMS reinforcement, with flexural strength between 20% and 100% higher than others, signs of good bonding with cementitious matrix, and the smallest loss in shear strength, independently of the mortar type [17, 21, 27].

Cracking, deformation, and microstructure: Musse et al. [27] tested a prone-to-cracking, low-strength mortar (flexural strength of 0.8 MPa), with the exposition of wall panels, reinforced with EMS, WMH, and polymer mesh, to thermal loadings. They evaluated the cracking behavior through thermography, maximum crack opening, and the ratio between total crack length and the panel area (known as cracking index, CI) relative to the unreinforced panels. The results (Table IV) showed that EMS presented the best tension distribution, with increased CI under high thermal loadings but with smaller crack openings. The polyethylene mesh produced fewer cracks, but with wider openings. Similar behavior is noticed in the shear strength parallel to the reinforcement and on the impact test results, with the square steel presenting the smallest crack openings under the impact (less than 0.05 mm). The same study also reported that cracking induced by thermal loading could be detected in non-reinforced panels using thermography, however, no cracking was observed if the panels were reinforced. The main failure mode in flexural tests consists of mortar cracking followed by mesh rupture. After mortar cracking, EMS and AFG presented good residual load capacity, and polymer meshes showed the lowest, very close to unreinforced situations [20, 21]. Accordingly to the model presented by Junginger et al. [20], mesh reinforcements are unable to provide enough resistance to prevent the crack formation in coating if the crack propagates from the concrete structure behind it. Although it can be useful for crack opening control and mortar detachment avoidance. EMD meshes may also have problems associated with corrosion due to the lack of galvanization in most samples, leading to expansive stresses and degradation of the mortar matrix. It is also noteworthy that WMH meshes may need a more fluid mortar, to ensure the impregnation of its thin wires avoiding adherence problems [21].

Strengthening and retrofitting

The behavior of masonry walls depends on the relationship between its component's properties and the efforts to which they are subjected. Reinforced coatings can be used to improve the performance of these elements in rehabilitation and retrofitting or to provide higher strengths under special load conditions, such as seismic activity [11-13]. The mesh reinforcement is usually applied in discrete parts of the buildings and may be used as emergency repair or as a permanent strengthening method [30]. Some noteworthy applications of mesh in cementitious coatings include the reinforcement of load-bearing masonry in buildings constructed with non-structural blocks, especially in cases of old popular housing buildings [48] when bricks and mortar have low adherence [42] or for reinforcement of cave dwellings [9]. And as retrofit for historic buildings, when the use of epoxy resins is not allowed or suitable, as in stone masonry or reversible applications [3, 30, 47, 49]. The revised documents also covered masonry rehabilitation, the increase of load capacity on structural bearing walls [11, 46], retrofit due to seismic activity [3, 7, 10, 12, 13, 22, 30, 45, 47, 49, 50], coating influence in compressive strength [6], and reinforcement of arches and masonry vaults [51]. A recent study also covered a detailed characterization of AFG meshes for reinforcement use [51].

Table IV - Summary results of different mesh types (data from [27]).

Test specimen (dimensions)	Property	Mesh type		
		Square steel	Polyethylene	Weaved steel
Prismatic (7.5x7.5x28.5 cm)	Relative flexural strength	+48%	+46%	+22%
	Relative shear strength	-1.7%	-29.5%	-26.7%
Masonry, 38 °C (2.5 cm coating)	Relative CI	-7.51%	+14.16%	+23.17%
	Crack opening	0.1, 0.3 mm	0.7 mm	0.4 mm
Masonry, 80 °C (5.0 cm coating)	Relative CI	+64.04%	+27.61%	+39.81%
	Crack opening	0.1 mm	0.3 mm	0.2 mm

CI: cracking index.

Although a lot of work has been done about the use of mesh reinforcements for masonry strengthening, there is, apparently, a lack of guidelines for the selection and dimensioning of such retrofitting methods, as noted in a study [22] that also presented a brief list of studies in the area. Regarding the use of similar dimensioning methods (e.g. reinforced concrete coating), significant adaptions need to be made, considering the differences in stiffness, strength, load-bearing capacity, and masonry contribution [46]. As a possible effect of this gap, the majority of analyzed studies (73.7%) proposed analytical models [11, 13, 46, 51] or finite elements simulations varying from simplified considerations in 2D to refined 3D models with masonry and mesh discretization [3, 11, 12, 30, 45, 50].

Reinforcement design: in 76% of the studies, the reinforcement was applied to both internal and external faces of masonry. The reinforcement layers were usually connected through the bricks, providing a beneficial confinement effect that opposes the crack's opening and propagation under compression efforts [51]. Fig. 6 shows a histogram of the reported coating thickness. Layers between 25 and 30 mm are the most used, with almost half of the studies within 10 to 20 mm. Although thicker layers are related to a higher mechanical strength of test walls, other variables such as mesh opening and the use of connectors are more significant for performance [6, 13, 45]. 94% of the studies employed connectors to fix the meshes, like L or U-shaped fiberglass stripes, metal bolts, or steel hooks, fixed mechanically or chemically by use of mortar or epoxy. These anchorage points are a critical part of the system as they prevent detachment during loading stages [42, 45], keep the correct geometry of the mesh inside the mortar during casting, and are important to the stress distribution and ductility of the walls [46], especially under discrete cracking repairs [10]. Tests and finite elements models (FEM) results showed that the lack of connectors, or the use of inadequate ones, can disable the reinforcement and the resulting masonry behavior become similar to an unreinforced situation [12, 46]. Stress concentration can also occur around connectors, leading to local failure of blocks [11]. Some authors [3, 12, 47] used an additional mesh layer and steel washers in the vicinity to avoid such occurrences, and deep studies of the design and influence of connectors are widely recommended.

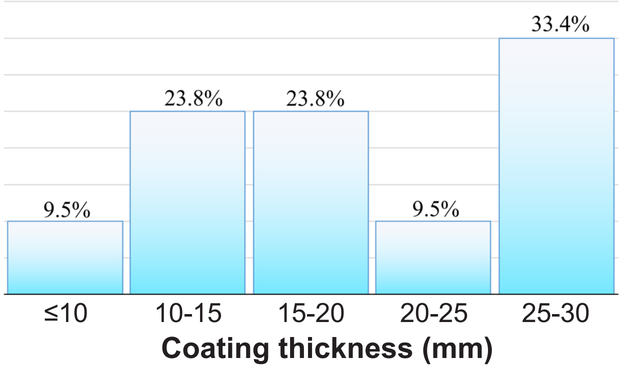

Figure 6: Histogram of reported coating thickness.

Regarding mesh position, 58% of the reported results were over the base, directly over the bricks, or with a thin mortar layer (less than 10 mm thick). 25% were at the half of mortar width and 17% at 2/3 of the layer width from the base. The masonry walls and prisms were tested under static and dynamic scenarios for compressive strength [6, 11, 48], shear strength [7, 12, 42, 50, 53], diagonal compression [22, 30, 45-47, 50], transversal loading [3, 13], and horizontal loading in the case of masonry vaults [51].

Fig. 7 shows the distribution of the reported coatings' strengths. Comparative studies suggest that stronger coatings provide slightly higher mechanical performance [30]. On the other hand, the behavior under load is significantly affected: sudden failure of masonry and coating debonding were reported with weak coatings (compressive strength <5 MPa), stronger coatings (around 23 MPa) presented successive and distributed cracking until failure, and stiffer coatings (36 MPa) specimens failed due to stress concentration in few cracks [11, 13]. The most employed reinforced material was AFG with square openings, varying between 5x5.9 mm and 99x99 mm, and diameters from 2.19 to 3.56 mm. Tensile strength was found between 530 to 1700 MPa and elastic modulus from 30 to 72 GPa. The best results were found with mesh openings between 33 and 66 mm [3, 12, 30, 45-47, 50, 51]. EMS is widely used, although the possibility of corrosion is a point of concern [46]. The openings varied from 50 to 200 mm, with wire diameters from 2 to 5 mm. The reported tensile strength was between 700 to 1040 MPa. Elastic modulus was not informed [6, 11, 42, 47, 48]. The crimped steel mesh used by Ghobadi et al. [10] had an average ultimate stress of 458 MPa. Polymer, basalt fibers, and hot-rolled ribbed meshes, with similar properties, were also used [9, 13, 22, 42].

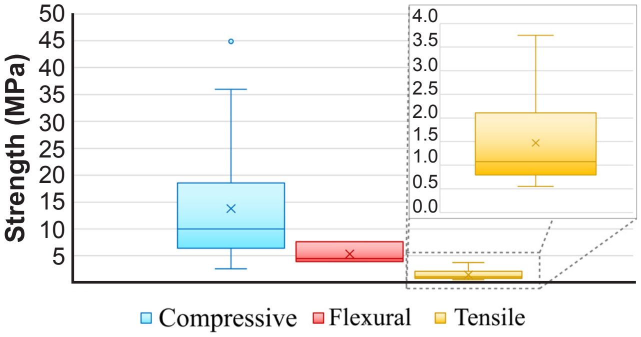

Figure 7: Distribution of reported coating mortar strengths.

Mechanical behavior: the observed results showed that mesh reinforcement coatings can effectively strengthen masonry walls under different load conditions. Strength gains with reinforcement varied between 20% to 400% in compression [11, 22], 20-200% in shear [30, 42], and 600% for transversal bending [3, 13]. Higher values are associated with the application of masonries with openings, unreinforced, or intrinsically weaker [42, 47].

Cracking, deformation, and microstructure: the reinforcement influence is even more evident during the deformation stages. The presence of meshes significantly affects the ductility of the walls [46], rising the load needed for the first crack [3], counteracting crack openings [47], and providing stiffer and stronger responses even in pre-damaged specimens [49]. The crack pattern also suffered significant changes when reinforcements were present. In general, unreinforced specimens presented cracks along the entire wall thickness, oriented vertically or diagonally depending on the load direction, mostly through brick joints, followed by the typical sudden resistance drop of brittle rupture [6, 11, 30, 46-48]. Differently, reinforced specimens exhibited smaller distributed cracking, beginning in the coating layer, next to the mesh wires, or between brick joints, then progressing through masonry [6, 22]. It is evident that the rupture mode is dependent on reinforcement properties, but the most reported occurrences include ductile behavior associated with higher deformation, monolithicity, significant residual strength [11, 30, 47, 48, 50], minimal brick damage [42], and load support by the textile until debonding or rupture [13, 22]. In the case of transversal bending, the specimens showed a single horizontal crack in the mid-height while unreinforced, but several parallel cracks if reinforced. The rupture only happened after mesh breakage [3]. Is observed that the total mesh strength is slightly different from the sum of individual wires, showing that the transversal mesh wires play an important role in the reinforcement's behavior. Nodes' connection also plays an important role in slippage avoidance and stress distribution but can lead to excessive cracking and debonding if the mesh opening is too small, due to the bond weakening between mortar layers as the effective surface area is reduced. The coating's failure pattern is also dependent on the effective bond length of the reinforcement, ranging from mesh slippage with mortar failure to complete mobilization of the reinforcement and composite failure only after wire rupture. Thus, the minimum length to avoid slippage should be determined by direct pull-out and lap-splice tests as it is highly dependent on the material and mesh geometry [16].

Modeling: the proposed analytical models showed good predictions on ultimate loads for design purposes, although some correction factors may be needed to match experimental observations [11, 46]. The FEM simulations produced good results with experimental and literature results, with errors within 10% and 20% [30, 45]. The models vary from simpler adaptions with 2D elements [12] to more complex involving associations of different materials and discrete mesh modeling [30]. Some FEM analysis suggests that thinner walls have more gains with reinforcement. Also, higher tensile resistance mortar coating and thicker layers should increase the first crack loading, while the higher tensile strength of mesh reflects in the ultimate bending resistance [3].

DISCUSSION

Although the results showed a high variability of test procedures and type of specimens depending on the desired application, is evident that mesh reinforcement promotes a better mechanical performance of mortar layers and masonries under different stress conditions, highlighting the potential for multiple applications. The reinforcement is associated with higher energy absorption and stress distribution along the layer, inducing ductile deformations in materials highly known for their brittle behavior. The reinforcement also contributes to higher energy dissipation capacity under seismic loads [7, 14, 19, 27, 43, 44, 46]. The technique execution is simple, relatively cheap, and does not require skilled labor [49]. The procedures for ferrocement applications, for example, are very similar to the known execution of reinforced concrete elements [49]. Some attention is needed for use in mortar coatings regarding the maintenance of geometrical criteria, as deformable meshes may end up folded, crumpled, or in the wrong position during mortar casting, compromising the reinforcement [21, 27]. Such occurrences can be prevented by using suitable connectors, whose relevance for system performance was already highlighted by the strengthening studies [42, 45, 46, 54].

Mesh positioned in the external part of the mortar layer (2/3 of its thickness) provided the best results in many scenarios involving coating mechanical and cracking performance, which can be attributed to mesh action in the tensile region of the composite. Such location is also logically interesting for façade applications since the external part is the most requested by thermal or impact loads. The middle of the layer is also an interesting position, as the thicker cover acts as a barrier for aggressive agents and protects the mesh from damage, enhancing durability. Some studies found little or no variation between these locations, but it is arguable if other effects, such as mortar properties and bonding conditions, were so influential that the position effect became negligible [15, 17]. Differently, most masonry reinforcement studies positioned the mesh directly over the base, as their main concern was the masonry's mechanical behavior. Such a position may be more appropriate for retrofitting situations, due to the removal of the previous coating and better fixation of the reinforcement [3, 30, 49]. Given the multitude of possibilities, design variables must be evaluated in detail for each application. A small opening mesh, for example, might be the best option for coating crack containment and composite tensile strength, but may also compromise the bonding area between mortar layers and result in premature detachment and spalling [14, 19]. Similarly, given one type of material, the mesh geometry, stiffness, wire diameter, and number of layers are of great concern. The WMH (also known as 'chicken mesh'), for instance, showed low contributions under different applications, while the EMS provided good results in most cases, so deep research is encouraged [17, 21, 22, 27, 43, 46].

The use of small grids yields good properties for composite applications, including high flexural strength and energy absorption. Also, the use of stiffer reinforcements provided better cracking control, as the stress needed for the first crack increased. An important point to be studied is the interaction between mesh and matrix, especially in the case of vegetal fibers, where some surface treatment may be needed to ensure chemical compatibility with the matrix. Is clear that the masonry type influences the failure mode of specimens, as hollow bricks behave differently from solid ones and rocks under stress, but the observed results suggest that it does not affect the effectiveness of the reinforcement, although different values of resistance increment were registered [13, 30, 46]. Several successful reinforcement applications were reported using multiple types of mortar. Properties such as mechanical strength and stiffness are highly dependent on the desired application, but a good bonding relationship with the chosen mesh is essential for all cases, especially if the reinforcement acts in the transition between different base materials. Direct-pull tests for the determination of bond length are highly encouraged [16, 21]. Some documents reported variations in performance when additions were incorporated into the mortars, but such results are out of the review scope [11, 48].

The use of connectors is predominant in strengthening applications because an independent behavior between the reinforced coating and masonry is not tolerated in such situations. However, attention is needed to possible stress concentration around the connection points, which could lead to premature failure. For façade applications, the use of connectors is an unexplored area, although some studies mentioned the use for detachment prevention and load support in the case of thick coatings. The behavior under load for strengthening applications appears to be directly connected to the mortar's mechanical strength. According to the findings, weak coatings should be avoided, as they resulted in sudden failure and mortar debonding. On the other hand, high-strength mortars present few cracks, with high stress concentration. Each situation should be accessed individually from a security point of view since the occurrence of successive and distributed cracking, obtained with medium-strength coatings, can be a useful and desired warning sign. For future research in masonry strengthening, is suggested the study of reinforcement stability under fire situations [48], more in-depth analysis of seismic out-of-plane capacity [13], a better understanding of the coating-masonry interface and bond lengths [3, 30], and the possible use of localized rebars in addition to the meshes in regions of stress concentration [42].

For façade design, it is important to observe the elasticity modulus of the reinforcement, as highly deformable meshes may not be able to control or prevent mortar cracking. The use of stiffer meshes usually results in more cracks but with smaller openings than a flexible mesh, demonstrating better stress distribution along the layer. Another relevant interaction to be studied is the relation between mesh opening and the adherence between mortar layers, because although smaller openings provide better tensile strength, the reduced mortar contact area may compromise the adherence of the whole layer. Such relations are still open and should be investigated by further research. Façade reinforcement can be applied in many ways, ranging from isolated applications (e.g. corners of openings or cracked regions) to full coverage of a wall panel (e.g. as support to a thick coating). Unfortunately, there are few guidelines to support the decision-making, which makes the process largely dependent on the designer's experience. The reviewed documents suggest an incipient state of the theoretical understanding, focusing on the analysis of mesh materials and their influence on the coating mechanical properties, and there are still numerous questions about the reinforcement technique that need further studies to be fully understood.

The interactions between mesh and mortar matrix at the microstructural level are extremely relevant to the performance of coatings in all applications described governing effects such as bonding, stress distribution, and cracking resistance. Few studies explored these details, focusing more on the macro effects of the reinforcements, which highlights the need for more research for future optimization of the technique. The findings indicate the need for standards and guidelines related to mesh reinforcements in mortar coatings. Some references revealed mentions of the technique in coating and tilling-related standards, such as the Australian standard AS 3958.1 [55], British standard BS 5385 [56], and Brazilian standard NBR 7200 [26]. Complementary technical recommendations may also be found in masonry and composite-related standards and seismic codes [12, 21]. It was also observed a lack of analytical and simulation models for façade coatings compared to the other applications. The development or adaption of existent models needs to care for the different phenomena acting on façades, especially due to the relevance that cracking occurrence has to this application, representing another potential area of study.

CONCLUSIONS

A systematic review on the use of mesh reinforcement in cementitious mortar layers, involving the analysis of 30 documents identified through a search in five databases without date restriction was conducted. The findings were associated with composite development, façade coating, and masonry strengthening or retrofitting. Most research was conducted on masonry and seismic strengthening, and the most recent findings from all applications agree that is still much to be researched and developed. From the results, the following conclusions can be derived: i) there is a need for guidelines for the selection and design of mesh reinforcements; a multitude of combinations of materials and influent variables are associated with the technique, highlighting the need for deep studies in both macro and micro scale in each application to the establishment of parameters for design; ii) FEM simulations and wider applications could benefit from a better understanding of the behavior between mesh and mortar matrix, especially in respect to bonding and stress distribution; the computational simulation is relatively new for façade applications, with no models proposed by the consulted references; iii) the use of meshes in mortar coatings is an effective, relatively cheap, and simple method for masonry retrofitting, reinforcement, and rehabilitation in diverse circumstances, including out-of-plane and seismic loads, or emergency repairs; the results showed great potential for changes in the failure modes of reinforced masonry, varying from sudden failure with mesh debonding to great stress concentration with fewer cracks; iv) for composite development, reinforcements with small grid opening and high elasticity modulus are preferred for the resulting higher tensile strengths; however, the relation between mortar matrix and the diameter of the wires, minimum mesh opening, and the number of layers need further studies, to ensure the avoidance of spalling and detachment; v) the study of mesh reinforcement's influence in façades is relatively new, and there is still much to explore concerning coatings' performance, design, and durability; the influence of coating thickness, and the relation between mesh opening and adherence between mortar layers, as well as that between mesh's deformability and cracking control, are of high interest for the application and demand for further research; also, no mention was made for mesh positioning, the texts suggest that usage is still very empirical, with few theoretical propositions; thus, further research is needed; and vi) there are significant changes in mechanical strength according to each application; most of composite studies used high compressive strength mortar with more than 39 MPa, while façade coatings stayed around 6 MPa; strengthening applications presented greater variation, ranging in between these two due to the multitude of materials involved. Such observations and future research possibilities presented could be of great value for the improvement of standards and formulation of guidelines on the use of mesh reinforcement in mortar coatings. The authors highlight that, although the present research was made as comprehensive as possible, it is not exhaustive on the topic, as the analyzed sample may not include other related documents that explore the research question but were not accessible or do not include the chosen keywords. Also, future studies should cover more in-depth aspects of the variables cited, including the reinforcement-matrix bonding interaction, coating failure mode, and mesh development for each application.

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