

Review

Use of Fiber-Reinforced Cements in Masonry Construction and Structural Rehabilitation

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Academic Editor: Alan Lau

Received: 4 December 2014 / Accepted: 27 January 2015 / Published: 4 February 2015

Abstract: The use of fiber reinforcement in traditional concrete mixes has been extensively studied and has been slowly finding its regular use in practice. In contrast, opportunities for the use of fibers in masonry applications and structural rehabilitation projects (masonry and concrete structures) have not been as deeply investigated, where the base matrix may be a weaker cementitious mixture. This paper will summarize the findings of the author's research over the past 10 years in these particular applications of fiber reinforced cements (FRC). For masonry, considering both mortar and mortar-unit bond characteristics, a 0.5% volume fraction of micro fibers in type N Portland cement lime mortar appear to be a viable recipe for most masonry joint applications both for clay and concrete units. In general, clay units perform better with high water content fiber reinforced mortar (FRM) while concrete masonry units (CMUs) perform better with drier mixtures, so 130% and 110% flow rates should be targeted, respectively. For earth block masonry applications, fibers' benefits are observed in improving local damage and water pressure resistance. The FRC retrofit technique proposed for the rehabilitation of reinforced concrete two-way slabs has exceeded expectations in terms of capacity increase for a relatively low cost in comparison to the common but expensive fiber reinforced polymer applications. For all of these applications of fiber-reinforced cements, further research with larger data pools would lead to further optimization of fiber type, size, and amount.

Keywords: fibers; masonry; mortar; earthen construction; rehabilitation; retrofit; concrete

1. Introduction

American Concrete Institute (ACI) committee 318's "Building Code Requirements for Reinforced Concrete" [1] does not yet recognize the enhancements that the fiber reinforcement can provide for the structural behavior of concrete elements (even the most common and well-researched type of fiber-steel). However, according to the State-of-the-Art report written by ACI Committee 544, use of fiber reinforced cements (FRC) is increasing around the world for a variety of applications. Some of the common applications of FRC include precast architectural cladding panels, slabs on grade, mining, tunneling, excavation support applications, and shotcrete among others [2]. Most of these applications utilize fibers in lieu of welded wire fabric reinforcement, and as a result, provide a potentially cost effective solution to the need for reinforcement in orthogonal directions.

While there has been extensive research on the topic for such traditional concrete applications, opportunities for the use of fibers in masonry applications and structural rehabilitation projects (masonry and concrete structures) have not been as extensively investigated. The common element in these two applications is that the base matrix may be a weaker cementitious mixture than other traditional concrete applications, therefore the effect of a smaller volume fraction of fibers may become more amplified. Further, in the case of masonry applications where the fiber reinforced mortar (FRM) is applied at the mortar joints, there may be additional requirements for aesthetics, compatibility, workability, and bond strength (unit to mortar). In the case of rehabilitation projects, bond strength and compatibility between FRC and the existing material may create additional design criteria. The research projects presented in this paper address these areas.

Scope and Goal of This Paper

The purpose of this paper is to summarize the findings of 10 years of research by the author and her graduate students regarding the use of fibers in masonry construction and masonry or concrete structural retrofit applications. Prior to delving into these studies and findings, a brief background review will be presented. This brief review of literature is provided to introduce the terminology and relevant common knowledge, and it is not meant to be an exhaustive resource on the subject. Readers who want to learn more about the background of FRC and related literature are encouraged to refer to the "State-of-the-Art Report on Fiber Reinforced Concrete" published by ACI committee 544 [2], as well as the many other valuable resources listed at the end of this paper.

2. Background on FRC and FRM

Fiber-reinforced cementitious composites differ according to the type of cementitious matrix employed to bind the reinforcing fibers: concrete, mortar, or cement paste. In order of increasing complexity: a cement paste is a mixture of cement and water, a mortar is a mixture of cement, water, lime, and fine aggregate (typically well-graded sand), and concrete is a mixture of cement, water, fine aggregate, and coarse aggregate. Cement paste, mortar, and concrete may also all include admixtures such as fly ash, silica fume, or high-range water reducers. According to Johnston [3], the inclusion of coarse aggregates in FRC typically decreases the fiber content of the material and consequently the reinforcement effectiveness of the fibers. Therefore, cements and mortars are more effective than concretes when fiber

inclusion is considered. It is the author's opinion that appropriate terminology should be used based on the specific type of cementitious matrix and the application of the material: fiber-reinforced cement, FRC, or FRM. Further, in this paper the abbreviation FRC will be used for applications in concrete rehabilitation and where there are no coarse aggregates in the base matrix, and the abbreviation FRM will be used for fiber reinforced mortar, *i.e.*, cement-lime base matrices in masonry applications. When a more general reference is made (covering both), the abbreviation FRC will be used.

The history of using fibrous materials in construction materials is nearly as long as the history of construction itself. Early use of plant and animal fibers in construction can be seen in the form of straws in adobe and horse or goat hair used in a binding mixture for masonry mortar and plaster. The modern use of fibers in cementitious mixtures start with a patent by Joseph Lambot in 1847. Naaman writes about the development of FRC between this patent until the 1960's [4]. Balaguru and Shah's book [5] on FRC also presents an informative and concise history on the development of the material.

Today, reinforcing fibers are available in a wide variety of materials and can be classified into four primary categories: steel (low carbon or stainless), mineral (glass or asbestos), synthetic organic (carbon, cellulose, or polymeric), or natural organic (fiber from plants or animals). Steel fibers are the most commonly used type of fiber for both structural and non-structural applications [6,7].

2.1. Why Are Fibers Used in Cementitious Materials?

Cement, mortar, and concrete mixes are brittle materials that are stronger in terms of compression, while weaker in terms of flexure and tension. When subjected to tension, these unreinforced brittle matrices initially deform elastically. The elastic response is followed by micro-cracking, then localized macro-cracking, and finally fracture. Fracture or cracking in hardened cementitious materials is common and it happens as a result of tensile stresses exceeding the small tensile strength of the matrix due to load effects, shrinkage, or other environmental factors. Brittle materials are considered to have no significant post-cracking ductility. Therefore, once a fracture happens, unless there is either traditional or fiber reinforcement to engage and augment the system with added tensile strength, the system experiences a sudden, brittle failure.

Possibly, the most significant enhancement resulting from the inclusion of fibers in cementitious matrices is the improvement in post-cracking behavior, which is typically evaluated by material toughness. Toughness can be quantified as the area under the load-deformation curve, which can be gathered as a result of a beam in 3-point bending test per ASTM C1609 [8,9]. There is also another ASTM testing standard, ASTM C1550 [10,11] specifically for measuring FRC toughness, which utilizes round panels.

Since the largest benefit of the inclusion of fibers is for post-cracking behavior, crack control is one of the most exciting applications of FRC. The fibers can prevent larger crack widths that could permit water and contaminant penetration and cause corrosion in reinforcing steel [2]. In addition to crack control and serviceability benefits, use of fibers at high volume percentages (5%–10% or higher with special production techniques) is reported to substantially increase the matrix tensile strength [12].

2.2. Important Factors Affecting the Performance and Characteristics of FRCs

The magnitude of the effect on fibers in the post-cracking behavior of FRCs can change from subtle to substantial, depending on a number of factors [2]. The author suggests grouping these factors into the following three categories:

1. Base matrix characteristics: matrix composition, aggregate size, strength;
2. Fiber characteristics: fiber type (elastic modulus, strength, surface bonding characteristics) and fiber size (length, diameter, and their ratio, *i.e.*, fiber aspect ratio);
3. Composite mixture characteristics: fiber content, distribution, and orientation.

Two of these factors, fiber content and fiber size, are discussed in further detail here, as the projects summarized in this paper mostly tested these variables in different applications.

Fiber content: The amount of fibers present in the FRC also greatly affect the resulting mechanical properties of the FRC. Because of the wide range of reinforcing fibers available, and a corresponding wide range of material densities, the fiber content of an FRC mixture is typically indicated by a volume fraction of fibers per unit volume of composite material [3]. Mehta and Montiero [7] classify FRC into three primary categories based on the volume fraction of fiber present in the FRC:

1. Low volume fraction (less than 1%) is used to reduce shrinkage cracking primarily in slabs and pavements.
2. Moderate volume fraction (between 1% and 2%) is used in structures that require increased energy absorption capability. At this volume fraction, the fibers increase the modulus of rupture, fracture toughness, and impact resistance of the FRC.
3. High volume fraction (greater than 2%) also known as high-performance or ultra-high-performance FRC. The increased amount of fibers in these mixtures requires the addition of admixtures to achieve practical workability of the material.

While it is more convenient to refer to the percentage as simply “volume fraction”, it should be noted that for actual mixture design, it is usually better to specify fibers by weight and fiber content by weight per unit volume of composite.

It should also be noted that in all of the projects summarized in this paper, a low volume fraction of fibers (1% or less) is used.

Fiber size: Equally important to the amount of fibers is the size of those fibers. ACI committee 544 suggest the following fiber size categories:

- Macro fibers are reinforcing fibers with lengths varying from 0.5 to 2.5 inches (12.7 to 63.5 mm).
- Micro fibers are defined as reinforcing fibers with lengths less than 0.5 inches (12.7 mm or smaller).

Following these definitions, previously published research work can be categorized into three general groups: studies on macro fiber reinforced cementitious mixtures, studies on micro fiber-reinforced cementitious mixtures, and studies that utilize a combination of macro and micro fibers (hybrid fiber use). A very brief summary of findings from these three groups of research are presented next:

Macro fiber use in FRC: There are research findings available for steel, glass, polypropylene, polyethylene, and even natural (date-leaf) macro fibers in a variety of mixtures [13–17]. Steel fibers are

found to improve ductility, compression, splitting tension, flexure, and shear [16]. Studies and results on other fiber types have not been as extensive or as conclusive as those on steel fibers.

Micro fiber use in FRC: The use of micro fibers as reinforcing may offer several advantages including lower costs, better control of shrinkage and creep, and improved workability due to the smaller size of reinforcing fibers [18]. However, the inclusion of micro fibers is also shown to reduce the compressive strength of the mix relative to plain mortar, due to increases in the air content of the mixture. The exact mechanism responsible for additional entrained air is not currently understood, but it may be due to the presence of both micro fibers and sand particles in the mixture [18].

Hybrid fiber use in FRC: Investigating the synergistic effects of combining macro and micro fibers or two different fiber types (steel and polyvinyl alcohol) is also considered in FRC research. The fundamental concept is that micro fibers are involved in early loading stages and increase strength by prohibiting micro cracks from merging and forming macro cracks. Once the capacity of the reinforcing micro fiber is surpassed, the macro fibers engage and increase the ductility of the composite material. An additional benefit of hybrid FRC is a decrease in water permeability due to increased crack control provided by the reinforcing fibers. Findings from pertinent literature on hybrid FRC include the following:

- According to Banthia and Soleimani [19], hybrid fiber reinforced concrete specimens exhibit flexural strength greater than conventional FRC mixtures and plain concrete.
- Sorelli *et al.* [20] illustrate that both the crack control and flexural strength characteristics of structural members can be improved using steel fibers of two different sizes.
- Lawler *et al.* [21] carry out a study combining steel macro fibers paired with steel or polyvinyl alcohol fibers and conclude that the combination of macro and micro fibers increases the flexural strength, crack control performance, tensile capacity, toughness, and resistance to fluid infiltration beyond what can be achieved by FRC incorporating only one size of fiber.

3. Summary of the Author's Research on the Use of FRM in Masonry Applications

The author has carried out extensive research on the use of FRM in masonry applications over the past 10 years. The majority of the research focused on the potential of FRMs as joint reinforcement in traditional fired clay or concrete masonry walls. A recent research project by the author also looked at use of fibers in compressed and cement- or lime-stabilized earthen construction, where fibers are considered both for the mortar and the units. Finally, inspired by the promising results of the FRM-only flexural strength tests of the first study (where the low-strength base matrices with a low volume fraction of fibers show valuable improvements in flexural strength and ductility), a novel method of strengthening two-way reinforced concrete slabs with a thin layer of FRC is proposed. Key findings from these research projects will be summarized here and references are provided for more in-depth review of the projects.

3.1. FRM as Joint Reinforcement in Traditional Masonry

An extensive research program on this topic was carried out by the author and her graduate students in three phases. In this section, first a background is presented to clarify the motivation and the basis of selection of key parameters. Then each phase is summarized with the tested parameters and main findings.

The main goal of this extensive research program was to investigate the potential of FRMs as joint reinforcement in traditional fired clay or concrete masonry walls. In these studies, the emphasis was on higher lime content and weaker mortar mixtures as the base matrix. The purpose of looking at weaker base mortars was twofold:

1. Positive effects resulting from the addition of fibers to the mortar would be more pronounced in weaker base matrices. Higher lime content means less cement in a cement-lime-sand mortar mixture and results in weaker mortars.
2. In these projects, the underlying scope was the potential use of FRMs in scenarios of rehabilitation or reconstruction of existing masonry structures. If FRM is to be considered for improving mortar strength in the rehabilitation of masonry, the binding matrix should be compatible with the original mortar mixture.

The compatibility of rehabilitation mortar in existing structures will be expanded on a little further here as it provides the main motivation for the start of this series of projects. Compatibility of the mortar should be considered in terms of mechanical properties, chemical properties, and aesthetic properties as appropriate to the philosophy of the given conservation project.

- (1) Compatibility of chemical properties: The binding matrix of the new mortar should be similar to the original mortar in composition to ensure mechanical and chemical characteristics that are compatible with the existing structure. Banfill and Forster [22] suggest that modern materials and repair techniques applied to historic buildings can cause deterioration due to the difference in permeability between historic mortars and modern mortars. For example, if the original matrix is lime based, the less porous cement mortar resists the transport of moisture through the masonry that in some cases may lead to deterioration. In the field, this is also considered the older structure's "breathing". The new cement-based mortars do not "breathe" as much; they "seal" the walls in a different way and may cause molding or other issues, as the moisture inside is no longer able to escape through the joints. While this may be fine for a newer structure where the sealed joints are taken into account by other means, such as cavity walls, it creates a "new" problem for the renovated structures.

Therefore, due to the variability in historic mortars, a primary consideration in the repair of historic masonry is the evaluation of the existing mortar's type, strength, and engineering properties. Then, the new mortar must be designed to be compatible with the existing mortar and masonry units to ensure a successful repair that will not damage the existing structure.

This creates a potential dilemma because most damaged masonry structures have cracked or entirely lost mortars, due to their low flexural capacity or lack of long term durability. Thus, repair with similar mortar matrices will not solve all of the structure's problems. The addition of reinforcing fibers to a similar binding matrix has the potential to solve this dilemma by utilizing a base matrix similar to the original, yet incorporating fibers. The new mortar would then be compatible with the original matrix, yet provide improvements in tensile and flexural strength as well as crack control and long term durability. This statement provides the guiding hypothesis behind the studies summarized here.

- (2) Compatibility of Mechanical Properties: Masonry is a heterogeneous material in that the overall strength of the wall is affected by the strength of mortar, strength of blocks, and the thickness of mortar joints. As such, it is important to keep in mind the strong unit, weak mortar philosophy

of masonry design. In rehabilitation projects, since repairing the mortar is easier and more economical than replacing masonry units, the compressive strength of the mortar should not be increased excessively during repair [6]. According to Johnston [3], fibers do not directly affect the compressive strength of the mortar. However, we found out that in some cases, as cracks develop parallel to the loading axis due to lateral dilation of the masonry wall under uniaxial loading, fiber-reinforced elements may exhibit an increase in strain capacity due to their ability to resist these cracks. However, the inclusion of micro fibers is also shown to reduce the compressive strength of the mix relative to plain mortar due to increases in the air content of the mixture. This means there is a reason for the mortar strength to both increase and decrease due to existence of fibers in the mortar. As will be discussed later, the author's observation on this topic is that any increase in the compressive strength of mortar due to addition of fibers is not significant unless a relatively large percentage of larger fibers is utilized. Therefore it is possible to maintain the weak mortar-strong unit balance with FRMs.

- (3) **Aesthetic Compatibility:** There are two common conservation and retrofit philosophies when historical structures are concerned. One suggests that the new materials should attempt to match the appearance of the existing materials as much as possible to preserve the overall building aesthetic, while the other suggests that the new materials should be clearly identifiable to the observers. In the author's experience, relatively newer structures with or without historical value tend to fall into the first category. In such cases, reinforcing fibers can be added to practically any binding matrix without any effect on the appearance. Furthermore, sophisticated mortar tinting solutions are commercially available, so it is possible to match the FRM aesthetic to a wide variety of existing structures. The interactions of different fibers within different matrices, however, should always be studied before a mixture is used on an existing structure.

The base matrices for the FRM studies summarized here are selected after considering these compatibility issues. Depending on the age and location of the structure, historic mortars either have a much higher lime content compared to cement content or they are entirely lime-based mortars. For example, as reported in a previous paper by Erdogmus and Armwood [23], the chemical composition of Roman mortar samples from an ancient structure was investigated and found to be approximately 1 part lime to 2.5 parts sand, with no evidence of pozzalana or similar cementitious material. Therefore one group of test specimens includes natural hydraulic lime-based mortar mixtures with compositions that are inspired from the above stated proportions. In the United States, weaker (large lime content) cement-lime mortar is more common in older masonry structures. Therefore, the second group of specimens studied includes Type N Portland cement lime (PCL) mortar, which are widely used for non-seismic applications of masonry today and are therefore commonly found in premixed packages.

Figure 1 presents the fixed and variable parameters as well as the different experiments carried out in each phase. An overview of these projects and their main findings follows Figure 1, but for further detail on these particular projects, readers are encouraged to refer to the following sources: [6,24,25].

The Phase 1 study was published in Skourup and Erdogmus [6]. It was the pilot study, in that it presented a proof-of-concept. This project utilized only type N PCL mortar as the base matrix. Three different lengths of polyvinyl alcohol (PVA) fibers were used in five different combinations and the findings were compared to a sixth mixture without any fibers (control mixture). Three types of tests were

carried out: compressive strength of mortar, flexural strength of mortar alone (Figure 2), and flexural bond strength between FRMs and standard solid clay brick units. The tests were in accordance with ASTM standards C39 for cylinder strength, C1018/C78 for flexural strength of 24 inch length mortar beams, and E518 for flexural bond strength of prisms [26–28]. Prism flexural strength for this phase will not be presented or discussed here, as this topic will be addressed later under Phase 3.

<p><u>Phase 1: Pilot Study</u></p> <p>Flexural Strength of FRMs Compressive Strength of FRMs Flexural Bond Strength- Prisms</p> <p><u>Fixed parameters:</u></p> <p>Type of fibers: PVA Type of binder: Type N PCL</p> <p><u>Variables:</u></p> <p>Length of fibers (6, 8, 18 mm) % of fibers: 0.6% or 1.2% →6 FRM Mixtures</p>	<p><u>Phase 2:</u></p> <p>Flexural Strength of FRMs (small specimens)</p> <p><u>Variables:</u></p> <p>Type of fibers: nano, PVA, nylon, horse hair Length of fibers: nano, 6, 8 mm % of fibers: 0.25% and 0.5% Binder type: Type N PCL (11 mixtures) and Hydraulic Lime (11 mixtures) →22* FRM Mixtures (Only 11 presented here)</p>	<p><u>Phase 3:</u></p> <p>Flexural Bond Strength- Prisms Shear Bond Strength- Couplets Compressive Strength of FRMs</p> <p><u>Fixed parameters:</u></p> <p>% of Fibers: 0.5% Type of binder: Type N PCL</p> <p><u>Variables:</u></p> <p>Type of fibers: PVA, nylon, Length of fibers: 6, 8mm Flow rate: 110% and 130% →10 FRM Mixtures</p>
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Figure 1. Summary of FRM Studies.

Phase 2 improved upon the first study and incorporated a larger number of variables, resulting in 22 total mixtures, 11 with type N PCL mortar and 11 with hydraulic lime mortar. Both for brevity and consistency of discussion, the lime mortar results are not discussed here, but can be found in references 24 and 25. The other difference in Phase 2 was that a novel method of testing with small specimens were utilized in the mortar flexural capacity assessments [24,29]. A comparison of the specimen size and setups is shown in Figure 2. As can be seen, while both tests aim to measure the flexural strength (*i.e.*, modulus of rupture) of beam-like specimens, there are differences between the specimens’ section moduli, maximum moment, and resulting moduli of rupture (Equations (1)–(4)).

$$S = \frac{bh^2}{6} \tag{1}$$

$$f_r = \frac{M}{S} \tag{2}$$

$$M_{Phase 1} = (P_1 / 2)a \tag{3}$$

$$M_{Phase 2} = \frac{P_2 L}{4} \tag{4}$$

where; S is the section modulus; b is the width of the specimen (4 and 2 inches for Phase 1 and 2, respectively); h is the depth of the specimen (4 and 2 inches for Phase 1 and 2, respectively), f_r is the modulus of rupture; M is the maximum moment; P_1 and P_2 are the maximum measured loads in Phase 1 and 2, respectively; a is the distance between one of the supports and the first point of the applied load in Phase 1 setup; and L is the span length between centerline of supports.

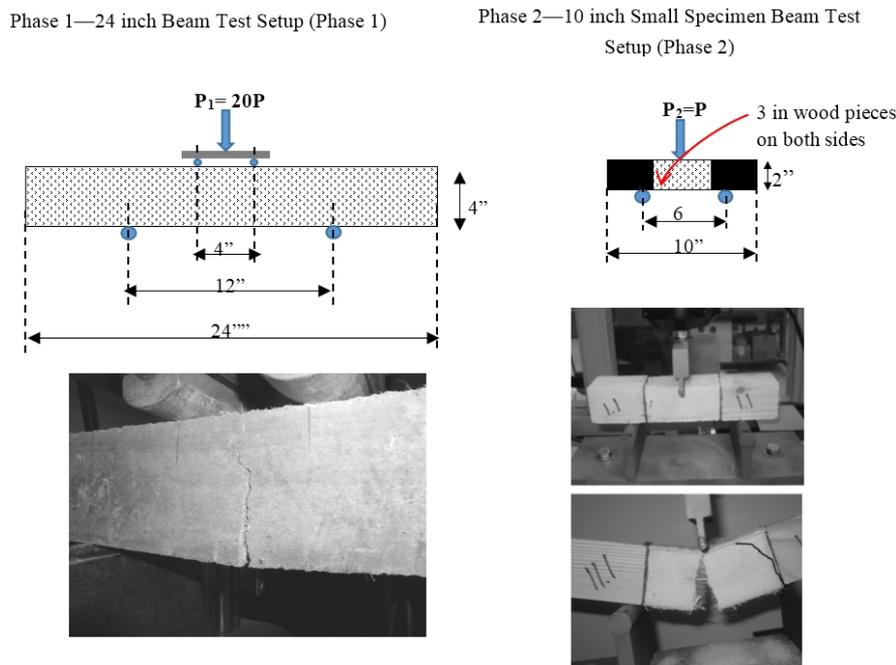


Figure 2. (Left) Phase 1: flexural test setup and photo of failed FRM specimen; (Right) Phase 2: small specimen flexural test setup and photos from the test

The results of Phases 1 and 2 are given in Tables 1 and 2, respectively. Using Equations (1)–(4) and including the ratio of average measured maximum load (P) between two phases (which is about 20), a normalizing factor or correction coefficient of 3.33 can be calculated by dividing the f_r from Phases 1 and 2 (Equation (5)):

$$\frac{f_r - \text{Phase 1}}{f_r - \text{Phase 2}} = \frac{M_1 / S_1}{M_2 / S_2} = \frac{(P_1 / 2)a}{2b(2h)^2 / 6} \div \frac{P_2 L / 4}{bh^2 / 6} = \frac{(20P / 2)(4)}{8} \div \frac{P(6) / 4}{1} = \frac{5}{1.5} = 3.33 \quad (5)$$

Table 1. Phase 1 test matrix and results.

Mixture	Fiber type	Fiber %	Specimen	F'_c (psi)	f_r (psi)
1	None	0	24 in beam	900	234
2	PVA 18 mm	1.2	24 in beam	630	206
3	PVA 8 mm	0.6	24 in beam	780	323
4	PVA 6 mm	0.6	24 in beam	970	434
5	PVA 18 mm + PVA 8 mm (hybrid)	1.2	24 in beam	1370	557
6	PVA 18 mm + PVA 6 mm (hybrid)	1.2	24 in beam	800	437

A column with modified values of modulus of rupture, *i.e.*, raw f_r values from Phase 2 multiplied by 3.33, is added to Table 2. Since the ratio of the average values of experimental modulus of rupture values measured in Phase 1 to those of Phase 2 is 3.96, we find that the modified values are comparable to Phase 1, despite the different testing method. This comparison also proves the more economical method of small specimen testing (Figure 2, right) to be a viable method for determining the modulus of rupture of FRMs. However, it should be noted that if the fiber sizes were any larger than the micro fibers used here, the effect of the fibers would be disproportionately high in the small specimens and could lead to erroneous results.

Table 2. Phase 2 test matrix and results.

Mixture	Fiber type	Fiber %	Specimen	f_r (psi)	Modified f_r (psi) (using a coefficient of 3.33)
1	None	0	small specimen	87	290
2	Nano	0.25	small specimen	69	230
3	Nano	0.5	small specimen	78	260
4	PVA 6 mm	0.25	small specimen	91	303
5	PVA 6 mm	0.5	small specimen	122	406
6	PVA 8 mm	0.25	small specimen	109	363
7	PVA 8 mm	0.5	small specimen	143	476
8	Nylon 6 mm	0.25	small specimen	77	256
9	Nylon 6 mm	0.5	small specimen	107	356
10	Horse hair	0.25	small specimen	69	230
11	Horse hair	0.5	small specimen	62	206

The following observations are made when both data sets are evaluated within their own Phase:

- Phase 1 proved the hypothesis that there will be a significant improvement in flexural strength of relatively weak PCL mortar mixtures by addition of fibers, and led to the following observations and suggestions:
 - As presented in Skourup and Erdogmus [6], ductility and toughness were also both improved by addition of fibers.
 - When looking at the compressive strength test results in Phase 1 (Table 1), hybrid macro-18 mm micro fiber mixtures could potentially be too much (Mixture 5), in that the strong unit-weak mortar balance may be negatively affected. Because Mixture 5 was also the least workable, it is not recommended for further consideration.
 - Both increases and decreases are recorded in compressive strength when fibers are added. It is suggested that the decrease in strength happens due the increases in the air content of the mixture relative to plain mortar, while the increase in strength happens due to fibers oriented horizontally stitching the micro-cracks caused by internal tensile stresses that occur as the test specimens dilate laterally during compression testing.
 - A useful general recommendation from Phase 1 was that micro fibers (rather than macro or hybrid fibers) at a 0.6% or lower volume fraction are better for masonry applications when all tested parameters (workability, modulus of rupture of FRM, compressive strength of FRM, and flexural strength of prisms) are considered.
- Phase 2 built upon the first phase and considered the following: only micro fibers or smaller (nano) at volume fractions of 0.5% or less. Since Phase 2 also included more variables, so the effects of these parameters could be individually studied. Figure 3 shows the effect of fiber content and fiber type on the modulus of rupture of FRMs, and the resulting observations are summarized below:
 - Nano fibers do not provide any benefits to the FRM. These small fibers almost identical in size to the cement particles and reduce the strength of the mixture by breaking bonds between hydrates.

- Likewise, horse hair fibers are ineffective for FRMs. The cause of this is determined to be the smooth and oily texture of the fibers resulting in pull-out at the failure surface instead of stitching the cracks.
- All other fiber lengths, percentages, and types (except 6mm nylon fibers at 0.25%) increase the flexural strength of FRMs.
- The optimal mixture for the flexural strength of FRM among all those considered in Phase 2 is that with 8 mm PVA fibers at a 0.5% volume fraction.

Phase 3 was a continuation of Phase 2 with a goal of testing other characteristics of FRMs that performed the best in the prior phase. The major contribution of this final phase was to look at the flexural and bond strength of FRMs as well as evaluate the effect of flow rate in the matter.

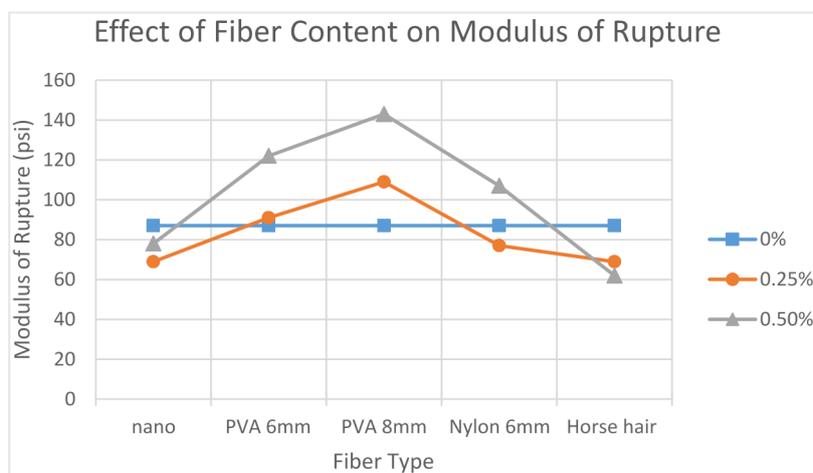


Figure 3. Effect of fiber content on the modulus of rupture for different types of fibers.

Flow of mortar was measured to understand the relationship between fibers and the water content, workability, and bond strength of FRM with masonry units. ASTM C1437-01 [30] was used for flow rate measurements. This test measures the mortar’s ability to spread from a condensed cylinder to a loose form in a matter of 15 s after being tapped 25 times. Per ASTM Standards, mortars tested in the lab should have a flow rate of 110% ± 5%, while a practical flow rate used for site applications is 130% ± 5%. As such, half of the specimens were at a target flow rate of 110% ± 5% and half were at 130% ± 5%. Henceforth, these levels will be referred as 110% and 130%. The testing procedure for measuring the flexural bond strength of masonry complied with ASTM E518-03 Standard [28] Test Method for Flexural Bond Strength of Masonry (Figure 4).

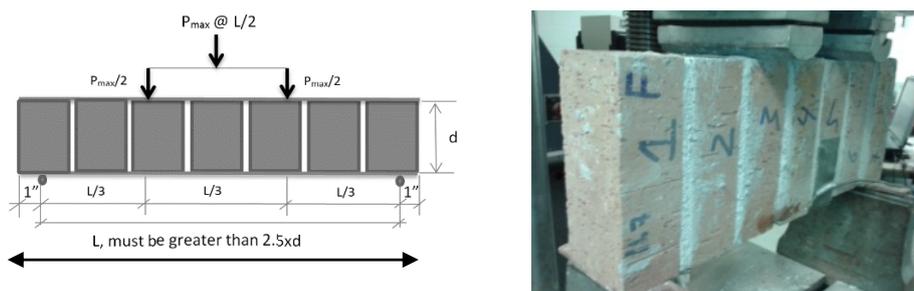


Figure 4. Flexural bond strength test-setup.

The shear bond strength test was adopted from Zhu and Chung [31]. This method involves applying a force in a direction parallel to the joint of the couplet, so that a closer representation of pure shear is achieved (Figure 5).

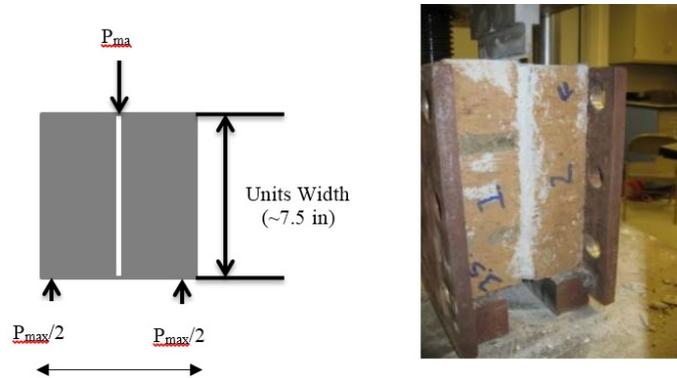


Figure 5. Shear bond strength test-setup.

Figures 6 and 7 present the results for flexural and shear bond strength tests, respectively, and a discussion of results follows.

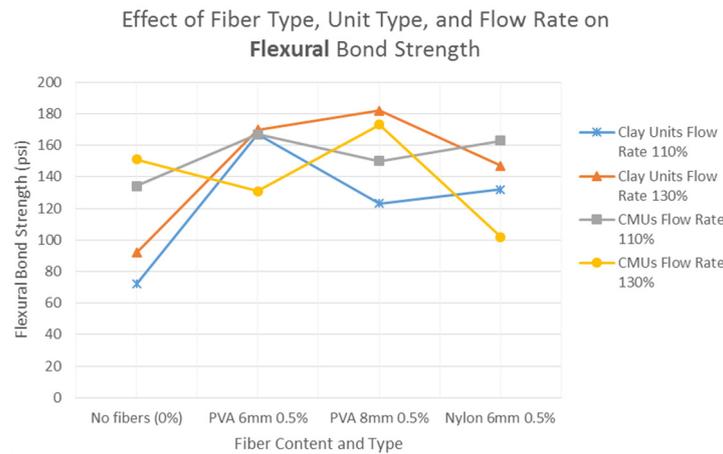


Figure 6. Effect of fiber type, unit type, and flow rate on flexural bond strength.

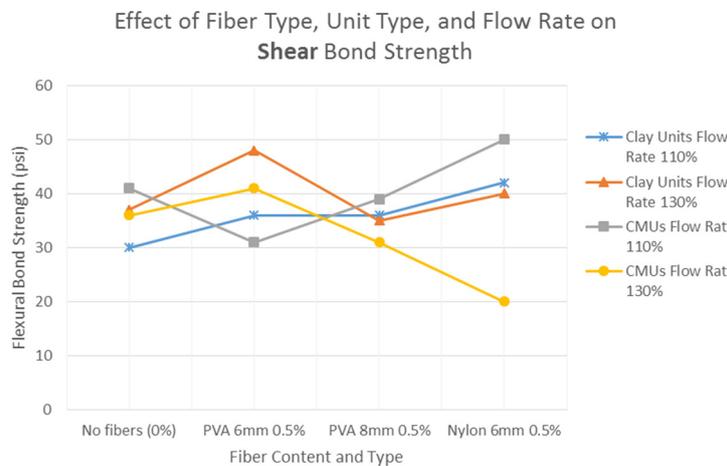


Figure 7. Effect of fiber type, unit type, and flow rate on shear bond strength.

- Observations on flexural bond strength results (Figure 6):
 - In general, clay units perform better with high water content (target flow rate 130%) mortars. CMUs did not present as consistent a relationship between water content and fiber use.
 - With clay units, at both 110% and 130% target flow rates, the flexural bond strength of FRMs were always greater than that of control specimens with no fibers in the mortar. It can be suggested that to keep the flow rate constant while adding fibers, one has to add more water, and as a result, the more absorptive clay units (compared to CMUs) and the mortar form a stronger bond. The fact that all of the 130% target flow rate values are higher than those of the 110% values also supports this argument.
 - With CMUs, at 110% target flow rate, addition of fibers always improved the flexural bond strength when FRMs are compared to the control mixture. However, at 130% flow rate, two out of three FRMs resulted in lower flexural bond compared to the control (no fiber) mortar. Only the FRM with 8 mm PVA fibers (at 0.5% fraction) presented improved flexural bond strength compared to the control mixture. While further research is needed, one explanation may be that the slightly longer fiber may be absorbing more water causing a drier mixture and improving the bond with CMUs.
 - At 130% target flow rate, the FRM with 8 mm PVA fibers showed the greatest increase in flexural bond strength both with clay units and CMUs, and therefore may be suggested as the optimal fiber type and length for this FRM water content.
 - At 110% target flow rate, the FRM with 6 mm PVA fibers showed the greatest increase in flexural bond strength, both with clay units and CMUs, and therefore may be suggested as the optimal fiber type and length for this FRM water content.
- Observations on shear bond strength results (Figure 7):
 - With clay units, at 110% target flow rate, the shear bond strengths of FRMs were always greater than those of control specimens with no fibers in the mortar. This finding is similar to that concerning flexural bond strength. At 130% target flow rate, both 6 mm PVA and 6 mm nylon fibers resulted in increased shear bond strength, while 8 mm PVA fibers resulted in reduced shear bond strength. While this suggests shorter lengths are more optimal, it should also be noted that another indirect variable between the two mixtures is the actual amount of fibers.
 - With CMUs, at 110% target flow rate, *i.e.*, drier mixtures, the addition of fibers seem to break bond in shear for both PVA fibers. Only an increase in capacity is observed for 6 mm nylon fibers. At 130% target flow rate, only 6 mm PVA fibers improved shear bond strength.
 - In general, shear bond strength results are not as consistent as those for flexural bond. However, 6 mm fibers demonstrated the best performance with both units. Specifically, 6 mm PVA fibers at 130% flow rate with clay units and 6 mm nylon fibers at 110% flow rate with CMUs showed the greatest increase in capacity. Most likely this has to do with the individual absorption characteristics of the two different types of fibers.

In conclusion, it may sound counter-intuitive to introduce fibers into a mortar joint, but the results show promise in expected behaviors (improvement in mortar ductility, flexural strength, crack control and therefore, durability), but also, positive results were achieved in terms of bond strength between

FRMs and units. Further research would be necessary to further optimize the type and content of fibers as well as the flow rate for each type of unit.

3.2. Use of Fiber-Reinforced Composites in Earthen Masonry Construction

A collaborative research project funded by the National Science Foundation is currently ongoing, led by the author as the Principal Investigator (PI) at the University of Nebraska, along with two collaborating PIs at the University of South Carolina and the University of Florida. The goal of this extensive research program is to experimentally and theoretically quantify the structural resilience of a novel fiber-reinforced earthen structural system that is engineered for load scenarios relevant to high wind regions. This engineered earthen structural system is composed of compressed and stabilized earth blocks (CSEBs) and compatible earthen mortars. CSEBs are created by using a mixture of soil and a dedicated percentage of cement or lime stabilization and applying pressure using either a manual or hydraulic block compression machine (Figure 8). Inclusion of recycled and non-biodegradable plastic fiber reinforcement is also considered in this project, with the hypothesis that the fibers will increase the overall flexural capacity of the system as well as resistance against local impacts. A side benefit of the fibers may be improved water-penetration resistance and long-term durability due to crack control. In both studies polyethylene terephthalate (PET) fibers are utilized with the idea that, if this application is proven successful, a new use would be found for the abundant and difficult to recycle PET bottles around the world (Figure 9).

A summary of two independent projects within the larger scope of the research program is given here, but for further detail on these projects, readers are encouraged to refer to the following sources: [32,33].



Figure 8. Process of CSEB making.



Figure 9. PET fibers.

3.2.1. Effect of Stabilization and Inclusion of Recycled Plastic Fiber Reinforcement on Flexural and Tensile Strength of Earth Blocks

In one of our sub-projects on this topic, reported in [33], five different types of compressed earth blocks measuring $14 \times 10 \times 3.5$ inches were tested in compression and flexure. A minimum of five

specimens were cast and tested for each specimen type. Table 3 summarizes the test matrix with materials and the results for the average of five specimens.

Table 3. Test matrix and results—CSEB Project 1.

Specimen ID	Description	Flexural strength (psi)	Compressive strength (psi)
1	Un-stabilized, no fibers (Control)	45	228
2	6% cement stabilized, no fibers	90	712
3	6% cement stabilized, 0.5% fibers	84	680
4	9% cement stabilized, no fibers	144	1517
5	9% cement stabilized, 0.5% fibers	122	1539

The positive effects of adding cement stabilization to the blocks are evident in terms of substantial increase of up to 220% and 565% in the flexural and compressive strength of the CSEBs, respectively. The addition of fibers produced both an increase and decrease in the compressive strength of the blocks. Such inconsistencies in the compressive strength of fiber-reinforced cementitious systems are expected based on published literature [6]. Finally, the addition of PET reinforcement into CSEBs resulted in a consistent reduction of the flexural strength compared to the stabilized but unreinforced counterparts in each case. This finding highlights the sensitivity of flexural strength to the voids and defects that are inevitably introduced when incorporating fibers. However, this project found that the fibers affect a change in the post-cracking behavior in flexure from brittle to damage-tolerant in that post-peak strength is established through a progressive failure mechanism characterized by fiber rupture and pull-out. The enhancement in damage tolerance is attained at the cost of a slightly reduced flexural strength compared to those of the stabilized but unreinforced counterparts [33].

3.2.2. Effect of Inclusion of Recycled Plastic Fiber Reinforcement on Water Resistance of Earth Blocks

Another small project carried out under the aforementioned National Science Foundation (NSF) research program was to test a series of CSEBs with and without PET fiber reinforcement in order to study the effects of water on CSEBs. With this research the project team aimed to offer solutions for the use and durability of CSEBs in wet climates. More specifically, the objective of this research was to investigate the effects of cement stabilization and fiber inclusion on water absorption through the block and the resistance to surface erosion of CSEBs when subjected to the action of heavy rainfall with wind. While a brief summary of the findings is provided here, for more detail, readers should consult reference [32].

Three sets of blocks were cast: (1) compressed but un-stabilized blocks (CEB); (2) compressed and cement stabilized (CSEB); and (3) fiber-reinforced, compressed, and stabilized earth blocks (FCSEB). Considering three specimens for each type of mixture, a total of 27 blocks were cast. For the production of CSEBs without PET fibers, four mixtures were tested where the cement content varied as 5%, 8%, 10%, and 15%. For the mixtures with PET fibers, the fiber length and volume fraction was kept constant at 3 inches and 0.25%, respectively; while the cement content varied similarly to those of CSEBs. The water content of the soil before production was determined to be around 23%. Because the amount of water added during block production is directly related to the block strength, it was kept as low as possible, resulting in a water-to-binder ratio of 25%. Table 4 presents further information on the design

of mixtures as well as results for the following tests: Absorption Test Results per ASTM C67-11 [34] and water pressure related surface erosion tests based on the procedure presented in Obonyo *et al.* [35].

Table 4. Test matrix and average results.

Specimen description	Block ID	Percent cement by weight (%)	Percent fiber by weight (%)	Water to binder ratio	Water absorption (%)	Average surface erosion (in/min)
Control	CEB	0	0	0.25	N/A	N/A
Cement stabilized	CSEB(5)	5	0	0.25	13	0.01
	CSEB(8)	8	0	0.25	11	0.001
	CSEB(10)	10	0	0.25	10	0.0011
	CSEB(15)	15	0	0.25	9	0
Cement stabilized & PET fiber reinforced	FCSEB(5)	5	0.25	0.20	16	0.0063
	FCSEB(8)	8	0.25	0.20	15	0.0046
	FCSEB(10)	10	0.25	0.20	12	0
	FCSEB(15)	15	0.25	0.20	14	0

The following conclusions are drawn from the test data and visual observations during testing:

- (1) Un-stabilized (CEB) samples eroded quickly when soaked in water during the absorption tests, proving these particular CEBs inappropriate to be used in highly wet climates. Part of this is due to prevalence of a special type of clay, *i.e.*, dispersive clay, in Nebraska soil utilized in this sub-project. This type of clay is highly unstable under water.
- (2) Cement stabilization indeed stabilizes the blocks, and helps with the negative effects of dispersive clays.
- (3) Cement stabilization is observed to reduce the water absorption of compressed earth blocks by 1% on average, while addition of fibers increase the water absorption by 2% on average. All specimens without fibers met the water absorption requirement suggested by International Labor Organization with less than 15% absorption rate. FCSEBs met the requirements only with 10% and 15% cement stabilization, and not with 5% and 8% stabilization. As such, it can be concluded that when 0.25% of PET fibers are added to the earth blocks, the cement percentage should be kept at 10% or higher.
- (4) All 24 specimens tested for surface erosion met the requirements, and none of the blocks recorded erosion greater than 0.04 in/min, which was designated as an upper limit by Obonyo *et al.* [35]. Cement stabilization contributed to the reduction of surface erosion, with 0.1% reduction per percent of cement addition.
- (5) After conducting the experiments presented in this project and reviewing the related literature, the following recommendations can be made:
 - Un-stabilized earth blocks (CEB) are not appropriate for water-prone areas. A minimum of 8% cement stabilization is suggested when dispersive clays are prevalent.
 - PET fibers (at 0.25% fraction) increase the absorption rate of CSEB, but the absorption rate stays at acceptable levels when the blocks are stabilized with a minimum of 10% cement content.

- At 10% cement stabilization without fiber reinforcement, there was zero penetration of water in the surface erosion test and only a 10% absorption rate. These blocks are a good option for water prone areas when only water absorption and water surface erosion are considered.
- Addition of fibers has a positive effect on improved surface toughness (zero surface erosion for various cement stabilization levels), and they also have an acceptable level of absorption with 10% or higher cement stabilization. When other structural benefits such as increased flexural strength, crack control capability and local toughness are considered, fiber-reinforced CSEB masonry is a very promising building construction solution, especially in projects where sustainability and/or economy are at the top of the priority list.

3.3. Structural Retrofit Applications of FRC

There are several cases where interventions to existing structures are deemed necessary: (1) a building might be scheduled for renovation; if the intended use of a structural system or element differs from its original design, or the code requirements have changed, any intervention in the system would require adherence to the new code that governs at the time of the renovation; (2) detected defects, as well as partial or full collapse of the structural elements may require retrofit.

For the last few decades, a common method of retrofit for reinforced concrete structures has been the use of fiber-reinforced polymer (FRP) laminates or sheets. Numerous studies have been published on the use of FRPs for increasing the structural capacity of reinforced concrete structural elements [36–39]. As such, the acceptance of FRP in providing a high-strength, lightweight, and economically viable method of structural rehabilitation is rapidly increasing [38].

While increasing in popularity, there are some drawbacks to the FRP strengthening of reinforced concrete structural elements: fire-resistance, unidirectional behavior, and a high cost (material cost of epoxy and FRP sheets, as well as labor cost of skilled labor applying the materials on site).

Therefore, the author carried out a study with her graduate students between 2006 and 2011, in which a novel method of strengthening two-way reinforced concrete slabs is proposed. This method, especially in terms of the base mixtures utilized, was inspired by the good results achieved with low-strength base matrix FRMs that were presented and discussed in Section 3.1. A summary of this project on concrete structure rehabilitation with FRC is given here, and further details can be found in Radik *et al.* [40].

The proposed method involves adding a thin layer of synthetic macro-fiber-reinforced fine aggregate cement (FRC) to the tension face, in order to increase the load capacity and ductility of two-way slabs subjected to out-of-plane bending in a relatively inexpensive manner. The FRC mixture was composed of 1% volume fraction of bundled polypropylene fibers in premixed type N Portland cement lime sand mortar mixture.

The comparison between fiber reinforced cement (FRC) and glass fiber-reinforced polymer (GFRP) retrofit is carried out considering the following parameters: feasibility, strength increase, and cost. Each test specimen was a square reinforced concrete slab of 5 ft × 5 ft × 6 in, with # 3 deformed mild steel bar reinforcement at a spacing of 6 in and at an effective depth of 4.31 in. Two types of “intervention” were then applied to the tension face of the two-way slabs: GRFP strips in two directions and FRC layers in three thicknesses: 0.5 in, 0.75 in and 1 in. A test matrix and summary of results are presented in Table 5, while Table 6 provides a cost comparison.

Table 5. Test mat Rix and results—FRC Project.

Specimens		Strengthening method	Ultimate load	Ultimate load capacity increase with respect to control slab	Maximum deflection	Energy absorption
Set	ID					
A	1	Control	57.5 kips	-	0.63 in	-
	2	0.5" FRC	68.0 kips	+18%	1.38 in	65.8 kip-in
	3	1" FRC	88.2 kips	+53%	1.16 in	80.9 kip-in
	4	GFRP	71.5 kips	+24%	0.47 in	21.9 kip-in
B	1	Control	59.2 kips	-	0.78 in	36.2 kip-in
	2	0.75" FRC	70.8 kips	+20%	0.99 in	53.5 kip-in
	3	GFRP—Ultimate Fail	86.0 kips	+45%	0.65 in	64.8 kip-in
		GFRP—Initial Rupture	-	-	-	35.6 kip-in

Table 6. Cost comparison between GFRP sheets and FRC layers.

Strengthening system	Unit cost	Capacity gained per unit cost	Percent difference
GFRP	\$6.70 per ft ²	890 lb per dollar	-
0.5" FRC	\$0.35 per ft ²	1900 lb per dollar	113%
0.75" FRC	\$0.53 per ft ²	1250 lb per dollar	40%
1" FRC	\$0.70 per ft ²	2800 lb per dollar	215%

Prior literature [37] reported that use of FRP can increase the flexural capacity of two-way slabs by up to 36%. Our study’s results are in good agreement with that study, as we found GFRP can increase the flexural capacity of two-way slabs by 24%–45%, with an average of 35%. The results of FRC strengthening, however, makes a strong case for this retrofit solution in terms of increase in load capacity, ductility, and energy absorption. FRC applied in thicknesses of 0.5, 0.75, and 1 inches on the tension face increased the ultimate load capacity by 18%, 20%, and 53%, respectively. Maximum deflection is always greater for FRC application when compared to the control case, and energy absorption (area under the load deflection curve) is greater than both the GFRP in initial rupture and the control cases.

As can be seen, while much research has been done on FRP strengthening of reinforced concrete systems and it is becoming more widely used, great potential exists for utilizing FRC as a means of strengthening structurally-deficient two-way reinforced concrete floor slabs. Experimental testing has shown that by applying a minimum 1-inch layer of FRC to the full tension face of a slab, a significant increase in the ultimate load carrying capacity and maximum deflection can be achieved for a lower material cost compared to conventional GFRP-strengthening. In addition, FRC strengthening possesses several favorable performance characteristics, such as increased ductility, inherent fire resistance, and more visible warning signs of an impending failure compared to GFRP. Furthermore, in a two-way out-of-plane-bending scenario, the weak axis, for which typically no flexural tensile strength is claimed by GFRP manufacturers, is vulnerable. The common solution to this problem in practice is to apply two layers of FRP perpendicular to each other; however, this makes the already expensive rehabilitation system twice as expensive and thus makes the FRC application a much more cost-effective solution to the bi-directional strengthening problem.

Results of this study are preliminary and are meant as a pilot study. The experimental program and analytical results show great potential in the FRC strengthening system, but further research is needed.

Additional specimens should be tested to increase the sample population and investigate the repeatability of the results. Material properties, such as fatigue, fire resistance, and bond should be further investigated, and the effects of varying fiber ratios should also be explored.

4. Conclusions

Based on the past 10 years of research carried out by the author, the following can be listed as the general conclusions:

- The main factors that should be considered when using FRM or FRC are:
 - Composition and strength of the initial cementitious matrix: as shown in both the masonry and the concrete structure application studies discussed in this paper, the lower strength matrices may benefit more from fiber addition compared to stronger base mixtures.
 - The amount of fibers: previous literature [7] stated only a medium volume fraction (between 1% and 2%) can affect energy absorption, modulus of rupture, fracture toughness, and impact resistance of the resulting FRC. Our studies have shown significant impact in these characteristics with 0.25%–0.6% volume fractions of fibers, confirming that when the base matrix is of a lower strength, the effect of fibers may be amplified.
 - The size of the fibers: our findings showed that nano fibers have negative effects on the FRM/FRC, and macro fibers do not fit well with masonry applications. Micro fibers should be preferred for masonry applications. For applications where additional improvements in strength and ductility are desired, hybrid mixtures of micro and macro fibers may be considered.
 - Geometry and surface texture of the fiber: as stated when describing the problems when using horse hair, excessively oily and smooth fiber surfaces tend to pull out instead of stitching cracks. Further, fibers can be bundled or in the form of single strands. For all of the applications discussed in this paper, except the last study concerning retrofit of reinforced concrete slabs, single strands are suggested.
- FRM use in masonry as joint reinforcement:
 - Compressive strength: previous literature [18] suggested that micro fibers reduce the compressive strength of the mix due to increases in the air content of the mixture relative to plain mortar resulting. We have noted both increased and decreased strength because of the following two potential behaviors in the specimen: (1) when the compression specimen dilates laterally, tensile stresses form in that direction, and the fibers that are oriented horizontally may then stitch the internal tensile cracks, increasing the compression capacity; (2) the fibers in general may cause air gaps in the FRM in addition to the naturally forming gaps in plain concrete. Plus, fibers oriented vertically may also break bond in horizontal tension and have no effect on vertical compression.
 - Flexural strength, toughness, energy absorption, and ductility of the FRMs themselves are typically higher compared to the control mixture, even with lower fiber percentages.
 - Bond strength with units in flexure and shear also seem to be positively affected from the addition of fibers, depending on the target flow rate (water content) and type of unit.

- All characteristics considered, a 0.5% volume fraction of 6 mm PVA micro fibers in type N PCL mortar appears to be a viable recipe for most masonry joint applications, both for clay units and CMUs, pending a larger data pool for optimization. In general, clay units perform better with high water content FRMs while CMUs perform better with drier mixtures, so 130% and 110% flow rates could be targeted, respectively.
- Fiber use in earth masonry
 - The particular project presented in this paper showed negative effects in the flexural and compressive strength of CSEBs with the addition of PET fibers, however, it is suggested that part of the problem is the long (3 inch) and very stiff (PET) fibers. Shorter and more flexible fibers would produce better results. Even with slightly reduced strength, though, the change in the post-cracking flexural behavior from brittle to damage-tolerant shows the promise of using fibers for local impact resistance.
 - The fibers also had a positive effect on the water pressure resistance (surface erosion resistance) of CSEBs.
- FRC as a retrofit technique in comparison to GFRP sheets
 - Test results have shown that by applying a minimum one inch layer of FRC to the full tension face of a slab, a significant increase in the ultimate load carrying capacity and maximum deflection can be achieved for a lower material cost compared to conventional GFRP-strengthening methods.
 - The FRC mixture utilized for such application be made of a relatively weak base-matrix, such as the pre-mixed type N PCL mortar used in this study.

Acknowledgments

The research projects covered in this paper were funded by a variety of sources, including NSF, National Center for Preservation Technology and Training (NCPTT), and University of Nebraska-Lincoln (UNL). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of these institutions. The author extends her deepest gratitude to the many students who participated in her research program over the years. Finally, a special thank you is extended to Brian Skourup for providing technical consulting and proof reading this paper.

Conflicts of Interest

The author declares no conflict of interest.

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