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Mortar Mix Design for Development of Low-Carbon Structural Upgrading Details for Masonry Buildings

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ABSTRACT

Portland cement production is a major contributor to global CO_2 emissions. Low-carbon cements, which typically involve the replacement of some of the ordinary Portland cement (OPC) in the mixture with supplemental cementitious materials (e.g., fly ash and/or slag), are a way to reduce the carbon footprint of masonry construction. Newly developed products can completely replace the OPC in cementitious materials. Such cement-free binders have very little CO_2 emissions in their production process. This paper investigates the use of a low-carbon binder to create a fibrous mortar mixture that can be applied on the face of concrete masonry blocks as part of a structural upgrading technique. Mortar mixtures are designed and tested with a low-carbon binder to assess their viability as an alternative for developing low-carbon structural upgrading details.

KEYWORDS

Structural Upgrading, Unreinforced Masonry, Engineered Cementitious Composites, Ecofriendly Geopolymer Concrete, Low-carbon Concrete/Mortar

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INTRODUCTION

Increasing sustainability in buildings and reducing carbon emissions from the construction industry can have a significant impact on the goal of reducing carbon emissions in Canada and worldwide. An effective way to increase sustainability in our current building stock is to encourage the renovation and upgrading of existing buildings that would otherwise be demolished to allow for the construction of a new building. Extending the lifespan of an existing building will, in most cases, have a lower carbon impact than demolition and new construction when a full life cycle analysis is considered. To further lower the carbon emissions resulting from building renovations and upgrades, low-carbon structural upgrading techniques should be developed and utilized.

Unreinforced masonry (URM) buildings make up about 6.4% of the total building stock in Canada, with almost all of these buildings being constructed pre-1990 [1],[2]. Many of these buildings have either reached or will soon reach the typical design lifespan. Retrofitting, including structural upgrades, will be necessary to extend the lifespan of these buildings. URM structures are constructed using masonry elements such as brick, stone or concrete masonry units (CMUs) but without any steel reinforcement. URM walls exhibit limited tensile strength because they do not contain the necessary reinforcement. As a result, these walls are vulnerable to buckling when subjected to high loads, making them less stable and more prone to failure in demanding structural conditions. Several upgrading techniques have been developed for the structural upgrading of URM walls, including the addition of vertical reinforcement, concrete overlays, Fibre-Reinforced Polymer (FRP) overlays, Fabric-Reinforced Cementitious Matrix (FRCM) overlays, and Fibre-Reinforced Concrete (FRC).

Concrete and other cementitious materials are known to have high compressive strength but low tensile strength and strain capacity. FRCs were developed by adding fibres with high tensile strengths to cementitious materials to improve their tensile properties. Originally, FRCs were made with short steel fibres to reduce the brittleness of concrete [3],[4] but FRCs have evolved to include the use of different types of fibres, including glass, carbon, synthetic materials, and natural fibres as well as a combination of different fibre types or length of fibres [5].

Engineered Cementitious Composites (ECC) are fibre-reinforced cementitious materials first developed in the early 1990s [6] that have a high tensile ductility and exhibit a strain-hardening response [5]. No coarse aggregate is used in a mix design for ECC, and as a result, an ECC mix typically contains 2-3 times more cement than a typical concrete mix [7],[8]. Cement production has a high carbon cost due to its production method where a mixture of limestone, clay, and sand are heated in a rotating kiln to very high temperatures to produce a cement clinker, which is then finely ground to produce the cement powder. CO_2 emissions are produced both from the combustion of fuel to heat the mixture and as a by-product of the chemical process in which calcium carbonate ($CaCO_3$) from limestone is converted into lime (CaO) [9]. In Canada in 2023, approximately two-thirds of the emissions from cement production were attributed to the chemical processes and the other third were attributed to the fuels combusted to heat the mixture [10]. The Cement Association of Canada [9],[10] reports that cement production accounts for about 1.5% of the country's yearly CO_2 emissions. These emissions are comparable to iron and steel production, which accounts for approximately 2% of Canada's CO_2 emissions but much lower than road transportation sector which accounts for approximately 17.5% [10]. Yoffe et al. [11] attributed approximately 90 Mt CO_2e to the construction industry in Canada in 2018, which would result in CO_2 emissions from cement making up approximately 12.4% of construction emissions. It is also reported that overall, concrete and cement production is responsible for 7% of annual global CO_2 emissions [9],[12]. Due to the high cement content in ECC, it is a very carbon-costly material. In order to reduce the carbon emission of ECCs, Eco-friendly Ductile Cementitious Composites (EDCC) were developed by replacing a large portion of the cement with supplementary cementitious materials (SCMs). ECC and EDCC have been shown to be able to effectively improve the structural properties of URM walls when applied to one or both sides of the wall [13],[14].

Engineered Geopolymer Concrete (EGC) is another eco-friendly version of ECC. EGCs use geopolymers, also referred to as alkali-activated materials, derived from industrial by-products such as fly ash, slag and metakaolin as the binder material to partially or fully replace cement. Yang et al. [15] were able to produce an ECC with reasonable mechanical properties using fly ash to replace a high percentage of cement (up to 85%). EGC can reduce CO_2 emissions by 50-80% compared to OPC concrete [16] while also reducing waste by reusing by-products from the construction industry. This paper investigates the use of a low-carbon binder to create an EGC-type mortar mixture that can be applied to the face of concrete masonry blocks as part of a structural upgrading project.

MORTAR DESIGN

A cement-free mortar has been designed with the intent of using it for structural upgrading of URM walls. The mortar was designed to have a high compressive strength, adequate tensile strength/strain, and good workability for hand-application on concrete block masonry walls. The binder used in the mortar mixes in this study is a slag-based (almost 100%), cement-free binder. This product completely replaces the cement in the mixture at a 1-to-1 ratio and produces very little CO_2 emissions. The other ingredients in the mixture include fly ash, sand, water and Polyvinyl Alcohol (PVA) fibres.

ECC refers to a family of materials known for their ductility, characterized by a tensile strain capacity that typically exceeds 2% [17]. Since 1992, a wide range of studies have been conducted on different ECC mixes. Li [17] proposes various mixes that enable the tensile strain-hardening behaviour of the produced mortar. These mixes replace 55% of the binder with fly ash and use a sand-to-binder ratio ranging from 0.36 to 0.55, with a maximum sand size of 0.25 mm. A fiber volume ratio of 1% to 2% and water to cement ratio of 0.25 is used. The proposed mix designs and other modified versions have been tested, demonstrating the microcracking and tensile strain hardening characteristic of ECC. EDCC [14] is another more sustainable modification of the ECC mix design. It uses a sand-to-binder ratio of 0.375 and a water-to-cement ratio of 0.27, yet this mix replaces 69% of the binder with fly ash and silica fume to make the mortar eco-friendlier. The maximum sand grain size used for this mix was 1.2 mm, and the fibre volume ratio was 2%.

The mix design used in this study is based on the primary mix design proposed by Li [17]. Consistent with previous mixes, the sand-to-binder ratio is set at 0.375. However, since the binder in this study is not ordinary cement and contains a high percentage of slag, different percentages of fly ash are used to assess its impact on the mix. Specifically, fly ash replaced 0%, 20%, or 40% of the binder material in different mix designs to improve workability and tensile strain. It is important to note that in EDCC, a higher amount of fly ash was used compared to ECC to replace more cement and enhance the mortar's environmental friendliness. However, since a low-carbon substitute for cement is already being utilized in this study, such high proportions of fly ash may not be necessary. Two different types of sand were used as aggregates in the mortar mixes, with maximum grain sizes of 2.5 mm and 0.25 mm. The fresh properties of ECC such as workability depend on water, sand, mineral additive, chemical additive, and fiber contents. In addition to the quantity of these factors, their type (i.e., sand particle size, roundness and sphericity) also plays a significant role. On the other hand, the average and maximum sand size influences the matrix fracture toughness which in turn affects the microcracking modes of ECC [17]. The water-to-cementing material ratio ranged from 0.27 to 0.40. The 6 mm long PVA fibres were included in the mixture to improve the tensile strength and ductility. No superplasticizer was added to the mixture since the cement-free binder already includes a superplasticizer.

The mix design proportions for the different mixes used in this study are summarized in Table 1. The values for fly ash are the percentage of binder that has been replaced with fly ash by weight, the amounts of sand and water are expressed in a ratio to cementing materials (binder and fly ash) by weight, and the amount of PVA is expressed as a percentage of the total volume of the mixture. Figure 1 shows a small batch of mortar that has been mixed to be used for property testing.

Table 1: Mortar Mix Design Proportions

Mix Number	Fly Ash	Sand Ratio	Sand Grain Size (mm)	Water	PVA
1	0	0.375	2.5	0.40	1%
2	20%	0.375	0.25	0.33	2%
3	20%	0.475	0.25	0.30	2%
4	40%	0.375	0.25	0.27	2%

Figure 1: Sample mixed mortar

PROPERTY TEST RESULTS

To evaluate the properties of the designed mortar, modified Vicat cone penetration tests and compression strength tests were performed on the mortar mixes. The Vicat tests were performed as per ASTM C780 [18]. This test measures the consistency of the mortar, with a higher value indicating a more flowable mortar [18]. The compression strength tests were performed on 50 mm cube specimens, as per CSA A179 [19], after 3 and 7 days to determine the compression strength of the mortar. The cube specimens are shown in the cube moulds in Figure 2 (a) and removed from the moulds in Figure 2 (b). The test results are summarized in Table 2.

Figure 2: a) Cube moulds for mortar compression tests and b) mortar cubes for compression tests

Table 2: Summary of Test Results

Mix Number	3-Day Compression (MPa)	7-Day Compression (MPa)	Vicat Cone (mm)
1	28.9	33.4	91
2	29.4	35.0	75
3	38.1	43.0	51
4	29.2	40.5	37

All mix designs demonstrated a compressive strength exceeding 28 MPa after just 3 days of curing. The 7-day compressive strengths surpass 33.4 MPa. For comparison, the average 3- and 7-day compressive strengths reported for EDCC were 21.3 and 33.3 MPa, respectively [20]. The results of this study indicate that the mixtures not only meet but surpass the threshold for good compressive strength, suggesting that they can perform well in structural applications. Mix 3 had a higher compressive strength due to the increased sand ratio. Comparing the 3-day compressive strength results obtained here with that reported for EDCC [20] suggests that the low-carbon slag-based binder used in this mix hardens and reaches its ultimate strength more rapidly compared to ordinary Portland cement (OPC). It was also observed that the mortar began to harden very quickly at times even less than an hour. This rapid hardening was more pronounced when lower fly ash ratios were used. In scenarios where low or no fly ash was incorporated, if the process of filling the molds extended, it was evident that the material was difficult to work with. The mortar examined in this study is designed to be used as an overlay or parging material on masonry walls. Therefore, achieving the right level of workability is crucial to ensure adequate adhesion and binding during hand application to vertical surfaces and for surface finishing. Unlike grout and concrete, where high workability is often desirable, the goal here is not to maximize workability. Excessively high workability can make the mortar too loose, reducing its ability to adhere effectively to the wall. Conversely, very low workability can make it difficult to properly apply and finish the mortar on the surface. The rapid hardening of these mortar mixtures will also affect the field application, requiring careful attention to handling for proper workability and effective adhesion. To maintain the desired qualities of the fresh mix, the mortar must be applied to the surface quickly before significantly hardening has occurred. Balancing these factors is essential for optimal performance.

The Vicat cone test results show a direct correlation with the W/CM ratio in the mix, with a higher flowability correlated with a higher W/CM ratio and increased fly ash content. The rheology and workability of mortars are influenced by both the liquid and solid phases. The liquid phase primarily provides lubrication, while the solid phase characteristics, such as packing density and particle shape, contribute to the rolling effect. The binder, a component of the solid phase, significantly affects the mortar's workability due to its shape. Replacing portions of the slag-based mortar with fly ash can enhance workability, as the round shape of fly ash particles offers a lubricating effect, as noted in literature studies [21]. In the lab, it was clear that mixes containing fly ash offered improved workability, making them more suitable for adhesion to wall surfaces. Each mix was visually inspected in the lab, and its ease of handling and application was evaluated. In the lab, the high workability and flowability of mixtures 1 and 2 made for a runny mortar that was impossible to hand-apply to a wall surface. Although Mix 3 had a good texture, it failed to adhere properly to a vertical surface, likely due to its high sand content. It was observed that the texture and workability of mixture 4 were consistent with the desired levels for hand-applying the mortar to the faces of the block walls while also allowing for easy surface finishing. A trade-off observed with Mix 4 was the slightly lower compressive strength. This reduction can be attributed to the higher ratio of fly ash used in the mix. As a pozzolanic material, fly ash takes longer to harden, resulting in increased strength at later stages compared to mixes with a lower fly ash content.

Displacement-controlled tensile strength tests will also be performed to measure the tensile stress-strain relationship to confirm that the mixture can produce a mortar with adequate tensile strength and ductility. The tensile strength test setup is shown in Figure 3.

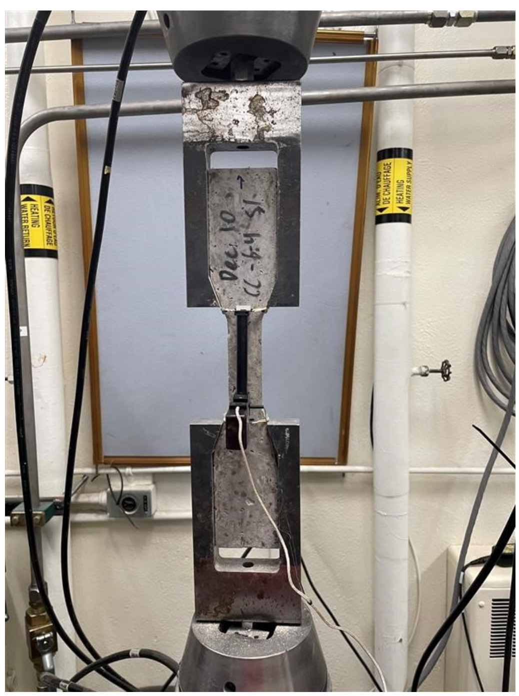

Figure 3: Tensile strength test setup

Conclusions

In this study, a mix design was developed and examined for a cement-free mortar to upgrade existing URM walls. This innovative design was created to address the unique challenges presented by these types of walls, with a focus on improving their load-carrying capacity without using traditional cement. The process included carefully selecting and proportioning alternative binding materials and optimizing the mix to ensure proper workability, adhesion, and performance. Through a series of laboratory tests, the effectiveness of the mortar was evaluated, providing valuable insights into its applicability for strengthening aging masonry structures. The results indicate that the fourth mix design, which uses a 40% replacement of the cement-free binder with fly ash and has a W/CM ratio of 0.27, achieves adequate compressive strength and has the desired workability for the mortar to be hand-applied to existing masonry walls. Further detailed testing will be performed by applying the designed mortar to the sides of masonry block specimens.

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