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EFFECT OF MORTAR TYPE ON THE SEISMIC RESPONSE OF PARTIALLY GROUTED REINFORCED MASONRY SHEAR WALLS

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ABSTRACT

Since the establishment of ASTM standard C91, masonry cement mortars have become widely used for masonry construction in low to moderate seismic regions. However, the Masonry Standards Joint Committee Code prohibits the use of masonry cement mortars in lateral force resisting systems for structures that fall into Seismic Design Categories D, E, and F. The general objective of this study is to examine the appropriateness of this restriction in light of past research and, if necessary, propose additional research required to fill any existing knowledge gap. Since information about the specific impact of the physical and mechanical properties of masonry cement mortars on the seismic response of masonry shear walls is limited, this paper primarily focuses on research that has identified the influence of mortar on the behaviour of masonry assemblages. In particular, this paper summarizes the available literature on in-plane pier response as well as the response of masonry assemblages under axial compression, flexural tension, bed joint shear and diagonal tension. The primary gap identified through this literature review was the lack of experimental research that addressed the response of reinforced masonry shear walls constructed with masonry cement mortar. To establish a comprehensive and efficient research program to fill this gap, the available literature related to the behaviour of partially grouted reinforced masonry shear walls was also reviewed and key factors that influence response were established. The paper concludes by summarizing the primary findings of past research and briefly outlining the proposed experimental program.

KEYWORDS: masonry cement, reinforced masonry, shear walls

INTRODUCTION

Following centuries of lime mortar use in masonry construction, portland cement-lime (PCL) mortars were developed in the late 1800's [1]. In the early 1900's, masonry cement (MC) was developed and patented (in 1917) and is now a generic product, primarily composed of portland cement or blended hydraulic cement and plasticizing materials. In addition, other materials are often added to improve mortar properties such as workability, setting time, and durability. Aside from providing desired workability and hardened mortar properties, masonry cement is proportioned in controlled conditions which greatly enhances its uniformity, alleviates the need for on-site mixing of portland cement and lime, and results in savings in construction time as well as more reliable mix proportions. Since the establishment of ASTM standard C91 for these products in 1932, MC mortars have become widely used for masonry construction in regions of low to moderate seismicity [1].

Currently, the Masonry Standards Joint Committee (MSJC) Code [2] prohibits the use of MC mortars in the construction of lateral force resisting systems for structures that fall into Seismic Design Categories (SDC) D, E, and F. Two factors have likely contributed to establishing and maintaining this ban: (1) MC mortars were not common in high seismic regions where seismic codes were developed and (2) research into the behaviour of ungrouted (solid or hollow) masonry assemblages has shown that MC mortars typically display lower bond strength than PCL mortars. Clearly, the first factor is social in nature rather than related to the actual seismic performance of shear walls constructed with masonry cements. The second factor, while well established, may not have a large influence on seismic performance. Consider that for SDC D, E, and F, all masonry is required to be reinforced and either partially or fully grouted (the MSJC Code requires a maximum reinforcement spacing of 1220 mm [48 in.]). According to past research, as the extent of grouting and reinforcement increases, the influence of mortar type and mortar unit bond diminishes [3]. This phenomenon is attributed to the continuity across the weak bed-joint planes, and the additional load path provided by the grouted cells and reinforcement. As a result, it is generally accepted that for fully grouted masonry this provision is overly restrictive; however, it is unclear at what level, if any, of partially grouted reinforced masonry this restriction is appropriate.

The study reported herein addressed this issue and focused on two primary objectives. The first is to summarize the available literature that addresses the influence of mortar type and grouting on the behaviour of masonry elements. This included investigations on masonry piers under in-plane loads as well as assemblages under axial compression, diagonal tension, and flexural tension. Close attention was paid to how the mortar type and extent of grouting affected the properties and the response of masonry to load. The second objective involves evaluating the validity of the code restriction (in light of past research) and recommending future research required to fill in any identified knowledge gaps. The primary gap identified throughout the literature review is the lack of experimental research that addressed the response of reinforced masonry shear walls constructed with MC mortar. To establish a comprehensive and efficient research program to fill this gap, the available literature related to the behaviour of partially grouted reinforced masonry shear walls was reviewed and key factors that influence response were established. The paper concludes by summarizing the primary findings of past research and briefly outlining the proposed experimental program.

EFFECT OF MORTAR TYPE ON RESPONSE OF MASONRY ELEMENTS

This section briefly outlines past research that addressed the difference between MC and PCL lime mortar in regards to the in-plane behaviour of masonry piers and the response of masonry assemblages under compressive, flexural tension, and diagonal flexural tension. The large size required to investigate the response of partially grouted masonry typically precludes the use of masonry assemblages. Therefore the literature regarding the effect of mortar type on the properties of hollow and fully grouted assemblages was summarized. The behaviour of partially grouted masonry, depending on spacing of grouted cells, falls between that of hollow and fully grouted masonry. The MSJC code allows linear interpolation between these two extreme conditions.

The only research located that specifically addressed the influence of using MC mortar instead of PCL on the in-plane response of reinforced masonry piers was reported by Johal and Anderson [4]. This study subjected 32 partially grouted reinforced masonry piers to in-plane loads applied through diagonal compression. Both clay (16 specimens) and concrete (16 specimens) masonry were investigated along with various brands of masonry cement. Each specimen consisted of a square pier section (approximately 812 mm [32 in.] by 812 mm [32 in.]) with spandrel beams along the top and bottom. All of the walls were reinforced and grouted at approximately 610 mm (24 in.) vertically and contained no horizontal reinforcement or grout within the pier section. The experimental results indicated that behaviour, in terms of cracking strength, ultimate strength, and failure modes, of the piers constructed with MC mortar were comparable to those constructed with PCL mortar. Based on these results, Johal and Anderson [4] concluded that the Uniform Building Code's (UBC) [5] restriction on the use of MC mortars for lateral force resisting systems was unfounded and should be lifted.

Drysdale et al. [3] discussed the effect of mortar type on the compressive strength of ungrouted clay and concrete masonry prisms. The experimental results showed that for both clay and concrete masonry the mortar properties influenced the compressive strength; however, this influence was far more pronounced for clay masonry. The effect was attributed to the lateral expansion of the mortar under uniaxial compression which places the units in biaxial tension transverse to the applied load. Two critical factors that affect the interaction of masonry units and mortar joints and explain the increased sensitivity of clay masonry were identified: relative unit-joint strength and relative unit height to joint thickness. In the case of clay masonry, the large differences in unit and mortar strength (i.e. a high unit-to-joint strength ratio) resulted in a larger differential lateral expansion between the unit and mortar, and in turn increased the biaxial tension stress in the unit. In addition, in clay masonry the unit height-to-joint thickness ratio is typically small and thus larger biaxial tension stresses develop within a given prism height. The lower sensitivity of concrete masonry compressive strength to mortar properties was attributed to the fact that concrete unit strength is comparable to that of the mortar and the unit height-to-joint thickness ratio is much larger than that of clay masonry.

In addition to compressive strength, the influence of mortar on the bond strength of masonry has been investigated by several researchers. Matthys [6] investigated the difference between the bond strength of ungrouted clay masonry constructed with MC and PCL mortars. This study concluded that MC mortars tend to display lower bond strength than the corresponding PCL mortars. Melander et al. [7] carried out a similar study using standard concrete bricks. The results of this study concluded that the lower characteristic bond strength was approximately 0.48 MPa (69 psi) for Type S MC mortar and 0.30 MPa (44 psi) for Type N MC mortar. Comparing with the bond strengths of PCL mortars, it was concluded that reduction factors of 0.6 and 0.5 be applied to the allowable bond strengths of Type S and Type N PCL mortars, respectively, when MC mortar is used. These factors were later adopted by the UBC [5]. In addition, Brown and Melander [8] carried out a similar study into the effect of PCL and MC mortars on the flexural tensile strength of fully grouted concrete masonry. The test results indicated that the flexural tensile strength of grouted prisms normal to bed joints is dominated by the grout strength.

Negligible difference in the flexural tension strength was observed regardless of unit type, mortar type or whether the mortar was MC or PCL. While these studies clearly established that MC mortar can be expected to display reduced bond strength for ungrouted masonry, it is important to recognize that unit-mortar bond is not simply a property of mortar, but rather a property of unit-mortar combination. Several past studies have found that interface bond is significantly affected by the physical properties of units such as absorption, surface texture and condition [3, 9, 10, 11].

Matthys [12] investigated the difference in diagonal tension strength of clay masonry constructed with MC and PCL mortars. The experimental program subjected 10 clay brick shear panels to diagonal compression loading in accordance with ASTM E-519. Both type S and N mortars were included in the study and MC manufacturers from each region of the US were represented. The walls constructed with Type S and N MC mortars displayed shear capacities of 0.94 MPa and 0.73 MPa, respectively, compared to 1.56 MPa and 0.95 MPa for the walls constructed of Type S and N PCL mortar, respectively. As a result it was concluded that MC mortars do not provide shear capacity equivalent to PCL mortars. However, it was also pointed out that both MC and PCL mortars provided shear capacities that greatly exceeded the UBC [5] allowables (0.110 MPa and 0.094 MPa for Type S and N, respectively).

EFFECT OF GROUTING ON PROPERTIES OF MASONRY ASSEMBLAGES

It is well established that grouted masonry assemblages behave considerably different than ungrouted or hollow masonry assemblages. Since the objective of this study focuses on partially grouted masonry, it is important to understand how the behaviour mechanisms of masonry assemblages are affected by grouting in order to gain insight into the possible influence of using MC mortar instead of PCL mortars for partially grouted masonry shear walls. The following section discusses the effect of grouting on the behaviour mechanisms of masonry assemblages subjected to compression, bed-joint shear, diagonal tension and flexural tension.

Drysdale and Hamid [13] studied the effect of grouting on the compressive strength of masonry prisms. The experimental results indicated that grouted masonry prisms have failure loads lower than those predicted using superposition to combine the capacity of the grouted area and the capacity of the unit area. This was largely attributed to transverse tensile stresses that develop in the unit due to wedging action of the grout as well as the lateral expansion of the grout due to the Poisson's ratio effect. This implies that the compression strength of grouted masonry can be expected to be less influenced by mortar properties than that of ungrouted masonry due to the dominance of the grout with respect to the failure mechanism. It was also noted that fully grouted specimens typically display more uniform behaviour with less scatter than ungrouted specimens.

Hamid et al. [14] investigated the influence of grouting on the bed-joint shear strength of masonry. This study concluded that grouted cells significantly increase the shear strength along the mortar bed joints due to "dowel action" of the grouted columns. The magnitude of this increased strength is influenced by the tensile strength of the grout and the percent solid of the units.

The influence of grout on the response of masonry subjected to flexural tension (normal to bed joints), diagonal tension (45^{o} from bed joints), and tension parallel to bed joints was studied by Drysdale and Hamid [15]. The experimental results found that grouting had a significant influence on the capacities of both flexural tension and diagonal tension since, in these cases, the failure plane crosses the columns of grout. Similar to the study on bed-joint shear capacity, it was concluded that the increase in tensile strength depends on the percent solid of the units and the tensile strength of the grout. For the case where tension was parallel to bed joints, negligible increase in capacity was observed, which was attributed to the failure planes occurring in between the grouted columns.

BEHAVIOUR OF PARTIALLY-GROUTED MASONRY ASSEMBLAGES

The studies discussed thus far have addressed only fully grouted or ungrouted masonry assemblages. Due to the size requirements of investigating the response of partially grouted assemblages, no literature that reports the behaviour of full-scale partially grouted assemblages was located. However, a few researchers have employed small-scale modelling techniques to investigate this issue. The following section discusses the results from these studies in regards to axial compression and flexural tension.

Using 1/3 scale concrete masonry units Hamid and Chandrakeerthy [16] studied the effect of partial grouting on compressive strength of concrete masonry. Specimens with grouted cells at 203 mm (8 in.), 406 mm (16 in.), 610 mm (24 in.) and 813 mm (32 in.) full-scale spacing were used. This study demonstrated that ultimate compression load per unit length of partially grouted walls increases and the variability reduces as the spacing of grouted cells decreases. The use of compressive strength based on gross area rather than net area was recommended since stresses are not distributed uniformly over the net area. Based on best fit of experimental results an empirical equation was proposed (Equation 1) to predict the compressive strength of partially grouted concrete masonry, f_{pg}', in terms of compressive strength of fully grouted masonry, f_g', and grouted cells spacing in inches, S.

$$f_{pg}' = f_g' \,(1.08 - 0.01S) \qquad \text{Equation 1}$$

In a related study, Hamid et al. [17] employed 1/3 scale concrete masonry units to investigate the tensile strength of partially grouted masonry. The test program subjected 15 wall elements with grouted cells at varying full-scale spacing (from 203 mm [8 in.] to 813 mm [32 in.]) to out-of-plane bending using the ASTM C1072 bond wrench. Results showed that the flexural strength was reduced as grout spacing increased and that this relationship was nonlinear. Based on best fit of the experimental results, the following empirical equation (Equation 2) was proposed to predict the flexural tensile strength of partially grouted masonry, f_{tpg}, in terms of the tensile strength of fully grouted masonry, f_{tg}, and grout spacing.

$$f_{tpg} = 4.4 f_{tg}\, S -0.75 \qquad \text{Equation 2}$$

Based on experimental results Hamid et al. [17] proposed analytical expressions to express the flexural tensile strength of partially grouted masonry, f_{tpg}, in terms of the strength of ungrouted, f_{tug}, and fully grouted, f_{tg}, masonry. Based on this study, it was shown that the flexural strength of partially grouted masonry is highly sensitive to grout spacing and that grout spacing in excess of 1220 mm (48 in.) has no significant influence on improving flexural tensile strength. This suggests that for grout spacing greater than 1220 mm (48 in.) the effect of grouted cells on flexural strength can be ignored and the wall can be treated as ungrouted from a flexural strength standpoint.

IN-PLANE BEHAVIOUR OF PARTIALLY GROUTED MASONRY SHEAR WALLS

As mentioned previously, a very limited amount of research has been identified that addressed the effect of mortar type on the in-plane response of either partially grouted or fully grouted reinforced masonry walls. Although the research identified [4] did indicate a negligible difference between the response of specimens constructed of MC and PCL mortars, the only primary variable included in the study was mortar type and thus the extension of these results is somewhat questionable. As a result, a knowledge gap exists that will require additional experimental research. To develop the most efficient and effective program to fill this need, the behaviour of partially grouted masonry walls must be clearly identified and understood. To that end, the following section summarizes some of the research in this area and identifies the key parameters that influence wall response.

Several studies have investigated the response of partially grouted reinforced shear walls including Matsumura [18], Chen et al. [19], and Yancey and Scribner [20]. Ghanem et al. [21] and Ghanem et al. [22] investigated the influence of reinforcement ratio and vertical stress, respectively, on the response of 1/3 scale partially grouted reinforcement masonry walls. Fattah [23] analyzed an extensive data set from past experimental studies and proposed a modification to the functional forms of an empirical equation originally proposed by Matsumura [18]. In a parallel study, Fattal [24] investigated the influence of critical parameters on the response of partially grouted masonry shear walls using the same data set. In general, this literature has identified three principal variables that exert substantial influence over the response of partially grouted reinforced masonry shear walls: vertical stress, aspect ratio, and the amount and distribution of vertical and horizontal reinforcement. The following conclusions summarize the findings:

- For the range of axial stress included in the studies outlined (0-1.8 MPa [0-260 psi]), the lateral strength of partially grouted masonry shear walls increased linearly and the displacement ductility decreased with increasing vertical stress. In addition, the level of vertical stress had a marked effect on failure mode. As the level of vertical stress increased, wall failures were altered from flexure to flexure/shear to shear.

- As the wall aspect ratio increased, the ultimate shear strength and cracking strength of masonry walls decreased. However, above an aspect ratio of 2.0, there was a negligible effect on the strength of masonry walls. For the range of aspect ratios investigated in the studies outlined (0.75–3.0) no correlation between deformation and aspect ratio was observed.

- For horizontal reinforcement ratios, ρ_h, in the range of 0%-0.2%, the ultimate strength and ultimate deformation of partially grouted masonry walls increased with an increase in ρ_h. In addition, for a constant reinforcement ratio, the distribution of the reinforcement had a significant effect on wall failure mode with failures progressing from shear to shear/flexure to flexure as the reinforcement becomes more distributed.

Although these investigations did not examined the influence of MC cement mortar on the response of partially grouted masonry shear walls, none of the investigations suggested that mortar type had any influence on wall response. Of particular note are the studies that focused on manipulation of test data from numerous studies. The models developed through these studies did not identify mortar properties or mortar unit bond as factors affecting response. Although perhaps not the most rigorous line of reasoning, this argument is consistent with the study reported by Johal and Anderson [4] and suggests that mortar type has a negligible influence on the response of partially grouted masonry shear walls.

CONCLUSIONS

Based on the review of available literature presented in this paper, the following primary conclusions are drawn:

- For masonry piers with reinforcement and grout at approximately 610 mm (24 in.) on centre and aspect ratios of 1.0, negligible difference in cracking strength, ultimate strength, and failure modes were observed between walls constructed with MC mortars and those constructed with PCL mortars under diagonal compression loading.

- For unreinforced ungrouted masonry, MC mortars tend to display a lower bond strength and diagonal tension strength than the corresponding PCL mortars. However, for unreinforced fully grouted masonry, the diminished mortar bond strength becomes negligible due to the influence of continuous grouted columns.

- Grouting the cells of masonry units provides continuity across the weak bed joints, reduces variability, and significantly diminishes the impact of mortar joint properties on strength and deformation capacity of grouted masonry.

- The extent of grouting affects the strength of partially grouted masonry in a nonlinear manner. That is, as the grout spacing is increased from 406 mm (16 in.) to 813 mm (32 in.) the contribution of grout does not diminish by 50%.

Based on the above findings, the authors find little evidence to support the contention that the use of MC mortar instead of PCL mortar will have a detrimental effect on the strength and deformation capacity of grouted and partially grouted (up to a spacing of 1220 mm [48 in.]) reinforced masonry shear walls. This conclusion is largely based on the extrapolation of assemblage data that suggests a diminished dependence on mortar properties when grout is introduced into the system. While this conclusion is strongly supported by a component study, several factors make the generalization of this study questionable including: the exclusion of influential variables such as aspect ratio and vertical stress, the highly idealized loading condition (that does not reflect actual boundary conditions of shear walls [25]), and the reinforcement and grout spacing of 610 mm (24 in.) (which is smaller than the maximum allowed). As a result, additional experimental studies may be required.

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