# University of Alberta

Recalibration of the Unit Strength Method for
Determining the Compressive Strength of Grouted Concrete Masonry

by

Michael David Ross

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Structural Engineering

Department of Civil and Environmental Engineering


Spring 2013
Edmonton, Alberta

**To my parents for their motivation,**

**My family for their inspiration,**

**And my friends for putting up with all of it**

**Abstract**

Using research that is now several decades old, the current Canadian masonry design standard, CSA S304.1-04, prescribes values for masonry design compressive strength based on the compressive strength of the concrete masonry unit and the type of mortar used in construction. The quality of unit production, masonry construction methods, and the theoretical understanding of masonry behaviour have improved significantly since these values were developed. As a consequence, current CSA S304.1-04 correlations between unit and masonry compressive strength values no longer reflect modern masonry construction and have been shown to be too conservative.

In this investigation, 140 concrete masonry prisms were constructed for compression testing to recalibrate the tabulated unit strength values. An update to CSA S304.1-04 is proposed which includes strength increases of 33-40% for prisms with type N mortar, 10-30% strength increases for prisms with type S mortar and low unit strength, and 0-12% decreases with high unit strength.

**Acknowledgements**

Without the support and guidance of Dr. Yasser Korany, this research would simply not have happened.

This research was funded by a Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research and Development Grant with the Canadian Concrete Masonry Producers Association (CCMPA). The author is financially supported by an NSERC Alexander Graham Bell Canada Graduate Scholarship. Concrete masonry units were supplied by CCI Industries. Inline Masonry, Precision Masonry, and Scorpio Masonry supplied the mortar, grout, and labour. The author is grateful for these contributions.

Brett Sturgeon's help as an undergraduate research assistant in the lab during the testing was invaluable and critical to completing the research program on time. Rizaldy Mariano, concrete lab technician for the department of civil engineering, was of great assistance as a resource for general concrete testing and for coming up with creative solutions for the testing requirements.

Finally, the structures lab technicians Greg Miller and Cameron West possess unique skills to keep the structures lab running that cannot be overstated.

# Contents

# List of Tables

# List of Figures

# CHAPTER ONE
# INTRODUCTION

## 1.1 General

The current Canadian masonry design standard, CSA S304.1-04 (CSA, 2004b), provides two methods to determine the design compressive strength $f'_m$ for grouted concrete masonry: prescribed values in Table 4 of the standard based on the compressive strength of the masonry unit and type of mortar, or using measured values determined from preconstruction testing of prisms under concentric axial compression. Although easier and less expensive to implement, current prescribed values are based on research that is now several decades old (Maurenbrecher 1986), and recent research has shown that the values are both overly conservative and uneconomical (Ip, 1994; Korany and Glanville, 2005; National Concrete Masonry Association, 2008).

Much has changed since the values in Table 4 were developed, such as the quality and properties of the units and mortar and the construction methods. There is now a much better understanding of masonry behaviour and a higher confidence in the design methodology compared to when the prescribed values were first introduced. The prescribed values in Table 4 of the Canadian standard were developed from a best-fit bi-linear regression between average concrete block compressive strength values and average prism compressive strength values computed from a database of prism tests, which were subsequently lowered by an arbitrary factor of 0.8 (Maurenbrecher, 1986).

This investigation is phase two of a program that was carried out in collaboration with the Canadian Concrete Masonry Producers Association (CCMPA), and included testing masonry prisms constructed of hollow and grouted concrete masonry units and type S and N mortars under concentric axial compression. Comparable prisms, but hollow rather than grouted, were tested in a previous phase (Gayed et. al, 2012).

By updating the prescribed $f'_m$ values in the Canadian masonry design standard to more accurately reflect current practices and reliability of concrete masonry, it is anticipated that the cost of masonry construction will decrease, leading masonry to become a more competitive and economically-viable construction alternative. This in turn will result in more diverse options available in structural design, and ultimately in large savings to owners and the Canadian economy.

## 1.2 Objective and Scope

The objectives of the experimental investigation are to assess the extent of conservatism in the prescribed values in the Canadian masonry design standard, recalibrate the correlation between the strength of concrete masonry units and the compressive strength of masonry prisms, and recommend new prescribed compressive strength values for concrete masonry construction that are more representative of measured strengths.

## 1.3 Methodology

Prisms were constructed by professional masons in the I.F. Morrison structural lab on the University of Alberta campus. Seven prisms were built for each unit and mortar combination in a running bond, three courses high, and one block in length and width. Normal stretcher masonry units were used as supplied from a local masonry producer. Prisms were tested using a 6600 kN MTS universal testing machine in concentric axial compression.

The concrete masonry units and mortar types used for the construction of the masonry prisms cover the full range of products currently used in masonry construction in Canada and the range of unit strength values found in Table 4 of CSA S304.1-04.

In total 140 prisms were constructed, and of these 102 were tested, in order to study the different possible combinations of five different block strengths as well as type N and type S mortar, both as Portland Cement Lime and Masonry Cement mixes. A minimum of five prisms for each group were tested.

In order to assess the extent of conservatism in the current prescribed values and to compare the results obtained from this study to available test results, an analysis of previously-published grouted prism test results was performed.

## 1.4 Thesis Organization

The thesis hypothesis and methodology is introduced and described in Chapter 1. Chapter 2 is a literature review of the results of available research on grouted concrete masonry and discusses an analysis of previously-published test results on grouted masonry prisms that was used to supplement and compare to the test results obtained from this test program. Chapter 3 describes in detail the methodology used for the construction, sampling, and testing of the specimens used in this research. The test results of materials and masonry prisms are presented and discussed in Chapter 4. Chapter 5 is a summary of the conclusions and recommendations.

# CHAPTER TWO
# LITERATURE REVIEW

## 2.1 Introduction

One of the most important factors in the design of masonry structures is the specified compressive strength of masonry, $f'_m$. The compressive strength of grouted concrete masonry is influenced by the interaction between its three main components: the concrete masonry units, the mortar, and the grout. Research into each of these three components of masonry and their effects on $f'_m$ is reviewed in this chapter.

## 2.2 Concrete Masonry Units

### 2.2.1 Effect of Unit Geometry

Concrete masonry units (CMU) are produced in a variety of shapes, sizes, and strengths. The most common unit used in construction in North America is 390x190x190 mm in size with two tapered cores, and is commercially produced in a compressive strength ranging from 10 MPa to 40 MPa, though the most common unit used in the construction of loadbearing masonry walls is 15 MPa (CSA A165). Test methods provided in CSA A165 and ASTM C140 are used in determining the characteristics of concrete masonry units as well as the specifications for these units.

Research by Kingsley and Atkinson (1986) has suggested that the compressive strength of grouted masonry prisms is sensitive to the ratio of core area to gross area of the concrete masonry units, but that no similar effect was noted for hollow masonry. Under certain circumstances where the grout strength was significantly higher than the unit strength and the core area approached 50% of the gross unit area, the prism strength was found to be higher than the constituent unit strength. The results for grouted masonry prisms were justified under the assumption that a stiffer grout would take a disproportionately large amount of the load, resulting in the maximum load of the prism being a weighted average of the two materials.

The stretcher units used in this research were 56.0% solid. Hamid (1978) found that the ratio of the thickness of the face shell to the width of the masonry unit did not have a significant effect on the compressive strength of grouted masonry as long as the ratio of net to gross area was kept constant.

Colville and Wolde-Tinsae (1990) determined that the geometry of the concrete masonry units, specifically the tapering of the webs, has an effect on prism strength. Tapering of the webs has been introduced in order to allow for easier mould removal and lifting by the mason, but the subsequent deviation in cross-sectional area throughout the prism height has been shown to have a negative effect on strength. This difference was found to be insignificant for hollow masonry as mortar is only applied along the face shells, where there is minimal difference in area along the height of the masonry unit. In grouted masonry, however, the tapering of the webs may restrict grout flow and create voids in the grouted concrete masonry or otherwise cause discontinuities in the grout cores, which can reduce the compressive strength of the prism (Colville and Wolde-Tinsae, 1990).

Drysdale et al. (1982) and Hamid (1978) recommended that the cells should be tapered as little as possible, or not at all, in grouted masonry due to the effect the tapers have on the prism compressive strength, however the practical requirements of the tapers for ease of construction continue to result in significant tapering. Hamid et al. (1986) performed tests on quarter scale masonry units and reported that the tapering in the face shells resulted in a 31% reduction to the unit compressive strength, which in turn led to a 27% decrease in grouted prism strength, and recommended that the practice of tapering the face shells be discontinued.

Khalifa and Magzoub (1994) suggested that the misalignment of webs can cause stress concentrations in the grout cores. Misalignments in the webs occur when masonry walls are constructed in a running bond, as the thickness of the center web is less than the total thickness of the unit edges and end webs. As well, when masonry half-units are used, their core area is less than the core area of the stretcher units, leading to further stress concentrations.

### 2.2.2 Effect of Compressive Strength

The compressive strength of concrete masonry units is most commonly determined by uniaxial compressive testing, but recent research has suggested that the use of sample coupons removed from the masonry units may also be useful in determining the compressive strength (Ganzerli et al., 2003; Thomas and Mujumdar, 2003). It was found that coupons with a height to thickness ratio of 3:1 and length to thickness ratio of 5:1 provided the best correlation between coupon compressive strength and full size unit compressive strength. It was also found that coupons cut from the top, middle, or bottom of the face shells gave different results, but no suggestions were given as to which location was the most representative for cutting coupons (Ganzerli et al., 2003).

Early research by Copeland et al. (1932) concluded that, for a given mortar, the strength of masonry walls formed a directly proportional linear relationship to the strength of the masonry units. Similar results were obtained by Roberts (1973) after a series of tests using different concrete masonry units. Research has consistently determined that the strength of the block is the most influential factor in determining the $f_m'$ value for masonry, but more recent research has suggested that though the prism strength increased with increasing block strength it was not a directly proportional relationship (Drysdale and Hamid, 1982).

Drysdale and Hamid (1982) suggested that accounting for the tensile strength of the concrete masonry unit provides a more reliable indication of prism strength, as tension is developed in the face shells of grouted masonry prisms during compressive loading due to the expansion of the grout, and is often the limiting factor during failure. Research by Chahine (1989) on masonry units from different suppliers similarly suggested that while the compressive strength of the units could be correlated to the compressive strength of hollow masonry prisms, a stronger relationship existed with the web tensile strength.

### 2.2.3 Moisture Content

Khalifa and Magzoub (1994) suggested that the compressive strength of concrete masonry units is sensitive to their moisture content, with air-dried blocks having a higher strength than saturated blocks. Their recommendation to test all masonry units in a saturated state, which was claimed to provide more consistent results, is not reflected in ASTM C140, which specifies that units be free of visible moisture or dampness at the time of testing.

The moisture content of the masonry units was shown to have an effect on the strength of grouted prisms as well, but was not considered to be a precise indicator of prism strength potential. Tests by O'Leary (1996) compared a series of prisms constructed with units of different absorption values ranging from 5%-17% in both an ambient and a wet state. It was determined that the total water absorption of the masonry units had almost no effect on the strength of the prisms, and that doubling the moisture content of the masonry units prior to grouting led to an approximate 10% decrease in prism strength.

## 2.3 Mortar

### 2.3.1 Physical Characteristics

Research by Melander et al. (1993) suggested that a principal difference between Masonry Cement (MC) and Portland Cement-Lime (PCL) mortars is their characteristic bond strength. Though both MC and PCL mortars can develop similar compressive strengths, the bond strength for MC mortars was found to be between 50-60% of that of PCL mortars.

Further tests by Brown and Melander (1999) on the flexural-tensile strength of grouted prisms, focusing on the difference in mortar strength, determined that flexural-tensile strength is dominated by grout strength, regardless of the difference in bond strength between mortars.

Although research by Farny et al. (2005) suggested that mortar quality is largely insensitive to water content, extreme variation in water content will produce an unsatisfactory bond between the mortar and the concrete units, where too much water may lead to poor masonry unit placement or inconsistent joint thickness, and mortar with too little water may not bond to the masonry unit at all.

**2.3.2 Effect of Compressive Strength**

Mortar used in masonry construction comes in a variety of types, but CSA S304.1-04 only allows for the use of types S and N for the design of loadbearing masonry. The properties of both of these mortars are governed by CSA A179-04. Type S mortar is intended for structural applications such as loadbearing walls, whereas type N mortar is intended for non-structural applications (Drysdale and hamid, 2005). Due to the absorption of water from the mortar by the masonry units and the confinement provided by the surrounding grout, the common practice of testing mortar cubes has been suggested to not provide realistic strength values for the in-situ mortar (Farny et al., 2005).

The interaction between mortar and the concrete masonry units has been the interest of much research in hollow masonry. Khalifa and Mazgoub (1994) suggested that reducing the block to mortar strength ratio reduces the lateral tensile stresses that develop in the masonry units due to deformational incompatibility, and indicated that choosing a mortar strength closer to that of the unit strength would provide a higher prism strength.

Hamid (1978) investigated the influence of Type N and S mortars and determined that there was little effect from the mortar strength on the strength of grouted prisms. Cheema and Klinger (1986) determined that the prism compressive strength was not highly sensitive to the compressive strength of the mortar used, unlike the influence of mortar strength in hollow masonry. Roman and Romagna (2002) agreed, and suggested that the mortar strength in a fully-bedded mortar joint in grouted masonry has little influence on the prism compressive strength, however in cases with a high grout strength, low mortar strength could become the limiting factor.

Khalaf et al. (1994) investigated the strength contribution of mortar joints to grouted prism strength by replacing the mortar joint with 10 mm thick polystyrene joints and determined that the presence of a mortar joint with a compressive strength up to 9 MPa led to nearly 100% increases in prism strength, as opposed to polystyrene joints (an effective mortar strength of 0 MPa), however at strength levels greater than 9 MPa the prism strength was insensitive to changes in mortar strength.

**2.3.3 Mortar Bedding**

Current Canadian masonry construction practice is to build concrete masonry with 10 mm mortar joints. Unlike hollow masonry, it has been suggested that the size of mortar joints had a minimal effect on the compressive strength of grouted masonry prisms (Cheema and Klingner, 1979; Khalaf, 1996). Hamid (1978) concluded that the mortar joint thickness had a significant effect on the compressive strength of ungrouted prisms, where a decrease in mortar joint thickness led to an increase in prism strength, but that no such effect was prevalent in grouted masonry.

The two most common types of mortar bedding are full bedding and face-shell bedding. Khalifa and Mazgoub (1994) found a number of differences between the two bedding types. In hollow masonry, face-shell bedding allows for bending effects to develop in the unsupported webs of the masonry units, allowing for cracking at lower loads than in full bedding. As a result, face-shell bedded prisms experience non-uniform stress-strain distributions with high tensile stresses developed in the webs of the units. This effect is minimized in grouted masonry as the grout will tend to fill in the voids under the webs.

## 2.4 Grout

### 2.4.1 Physical Characteristics

The Canadian masonry design standard CSA S304.1-04, apart from specifying target strengths for grout in masonry, does not prescribe a preference between coarse or fine grout, as long as the clear spacing in the grouted core is at least 50 mm. Guo (1991) and Hedstrom and Hogan (1990) determined that the presence of coarse aggregates in the grout leads to higher prism strength than fine grout, though the effect is reversed if the grout contains rounded or smooth-surfaced aggregates (Dhanesekar, 2004).

### 2.4.2 Compressive Strength

CSA S304.1-04 currently specifies the use of a very fluid grout with a slump of approximately 200-250 mm, leading to a minimum compressive strength of 10 to 12 MPa, for fine and coarse grout, respectively, for test cylinders cast in non-absorbent molds. Values for grout strength inside a prism have been found to be approximately 50% higher than equivalent strength values determined from non-absorbent testing, due to the absorption of water from the grout by the concrete masonry units (Hedstrom and Hogan, 1990; Sturgeon et al., 2013). Though not required by CSA S304.1-04, ASTM C1019-11 outlines the use of a mould created from concrete masonry units to determine a more accurate value for the in-situ grout compressive strength. This method has been determined to be within 10% of the true grout compressive strength (Hedstrom and Hogan, 1990).

Previous research (Ocean Technical Report, 1975; Drysdale and Hamid, 1979; Bexton and Tedos, 1989; Sturgeon et al., 1989) has suggested a wide range for the ratio of in-situ to non-absorbent cylinder grout strength, but this ratio has consistently shown an increase in in-situ grout strength relative to the cylinder specimens ranging from 1.2-2.2.

### 2.4.3 Influence on Prism Strength

Grouted concrete masonry has been shown (Drysdale and Hamid, 1979) to have a lower $f'_m$ value than hollow concrete masonry, though a grouted concrete masonry prism will resist a higher axial force than an equivalent hollow prism. Chahine

(1989) reported a decrease of 30-35% in the compressive strength of grouted prisms relative to hollow prisms, and that the compressive strength of grouted prisms was significantly lower than the strength of prisms constructed of solid masonry units even though the strength of the solid units was slightly lower than that of the hollow units. It has been suggested that a major cause of this effect is the deformational incompatibility between the grout and the concrete masonry unit, caused by a relatively high Poisson ratio in the grout. This has been observed to lead to tensile splitting of the block face shells and premature failure of the prisms (Hamid et al., 1978; Drysdale and Hamid, 1979; and Cheema and Klingner, 1986).

As a contributing factor towards $f'_m$ in a masonry assemblage, increasing grout strength has been determined to be an inefficient way of increasing the overall masonry strength (Cheema and Klingner, 1979; Roman and Romagna, 2002). It has long been argued that the simple superposition of strengths between these components is not a valid approach for determining the ultimate compressive strength of grouted masonry assemblages (Hamid et al., 1978; 1979).

Designers have often chosen grout mixes with the intention of developing a grout with a similar compressive strength as the masonry unit, but researchers have suggested that matching deformational characteristics of the grout, and not strength characteristics, is a more effective way of increasing $f'_m$ strength through grouting (Hamid, 1978). Khalaf et al. (1994) suggested that this deformational compatibility could be obtained by using a grout with a compressive strength of 45-50% higher than the concrete block, and Boult (1979) suggested that, under these conditions, a resulting prism could have an ultimate compressive stress higher than any individual constituent component of the masonry prism due to the mutual support provided between the masonry units and the grout.

Improved prism performance has been noted to occur when the stiffness is the same for the grout and for the block (Khalifa and Magzoub, 1994). If the grout is more flexible than the unit, lateral tensile stresses may develop in the mortar, and maximum vertical stresses in the blocks will increase as lateral stress in the grout increases. Horizontal tensile stresses will develop in the webs and face shells of the block as it restrains the expansion of the more flexible grout, causing bursting stresses and thus lowering prism strength. Alternatively, when the grout is stiffer than the units, stress concentrations may develop at the interface between the grout and the unit due to the bond between the components and cause premature failure.

## 2.5 Prisms

### 2.5.1 Prism Height

The Canadian masonry design standard CSA S304.1-04 specifies that a minimum of three-course high masonry prisms must be tested when establishing $f'_m$ for grouted masonry, and that the ratio of height to thickness of the prism must be at least 2.0. Although many masonry standards permit the testing of prisms consisting of only two blocks, the majority of researchers have recommended against this, suggesting that at a minimum of three courses the restraining effects of the machine platens are minimized, and a realistic failure response can be obtained in the center course (Maurenbrecher, 1978; Fahmy and Ghoneim, 1995). This is desirable in order to ensure that the failure mode is similar to what would be observed in full-size walls.

It has also been suggested by Boult (1979) that although in general an increase in the height-to-thickness ratio of the prism does decrease its compressive strength, there is no significant difference in the prism strength between prisms that are three to five units high, and prisms that are twelve units high. Due to the preference to perform research efficiently, three unit high prisms are often used and produce satisfactory results.

Using results from testing on prisms of varying height-to-thickness (h/t) ratios, masonry design standards have developed correction factors to relate the compressive strength of short prisms to taller prisms. For instance, a prism height-to-thickness ratio of 5 is used as a base point in CSA S304.1-04, and the strengths of any prisms with lower h/t ratios are decreased in accordance with the factors given in Table D.1. Prisms with h/t ratio values between 5 and 10 are assumed to have no difference in strength, similar to the observations by Boult. However, Maurenbrecher (1985) later found that there was a reduction in strength at high h/t ratio values, with a further 18-26% reduction in axial compressive strength in prisms with an h/t ratio of 10 relative to prisms with an h/t ratio of 5.

### 2.5.2 Bond Pattern

Numerous researchers have tested the effect of bond pattern on grouted concrete masonry. Hegemier et al. (1978) tested five course grouted masonry prisms in a running bond with face shell mortar bedding, and found a 16% decrease in strength relative to a stack bond. Maurenbrecher (1980) similarly found a 13% decrease in compressive strength, and Kingsley and Atkinson (1986) found that a running bond pattern leads to 11% decrease in compressive strength for grouted prisms as opposed to a stack bond.

However, other researchers came to different conclusions regarding the influence of the bond pattern. Hedstrom (1961) found that the effect of the bond pattern was not significant, and Hamid (1978) similarly found no significant effect of the bond type on the compressive strength for grouted prisms. Guo (1991) argued that Hamid used masonry units with a different shape than is currently used, permitting better alignment of the webs even in a running bond.

### 2.5.3 Test Requirements

As the requirements for the construction, storing, and testing of three-unit high masonry prisms made with full units can be extensive, the possibility of testing specimens on a smaller scale has been investigated. Long et al. (2005) found prisms constructed of half-size units produce results similar to prisms with full units with the same material strength, though this modeling method is not currently allowed under CSA S304.1-04. Experimental results by Khalaf et al. (1994) suggested that testing prisms constructed with half-units, as opposed to half-size units, overestimates the value of $f'_m$ by up to 25%, due to differences in the height-to-thickness ratio of the prism and the mortar bedded area.

Prisms that are not uniformly smooth or level when tested can create eccentric loading cases which reduce their apparent strength, and as a result the ends of the prisms are capped to reduce this effect. The current procedure under CSA S304.1-04 requires a capping material that is stronger than the masonry prism to allow for a uniform loading and to ensure that failure does not occur within the capping material. As with unit testing, the capping process can be simplified by only using flexible fibreboard, however this has been shown (Maurenbrecher, 1980 and 1985) to result in an apparent reduction in the compressive strength of the prism.

### 2.5.4 Curing

Thompson et al. (2002) performed an extensive series of tests on prisms at fourteen various ages of curing in ambient laboratory conditions between 1 and 56 days following grouting. The tests showed a strong trend where prism strength depended on the natural logarithm of time since curing. The authors further developed a prescriptive formula based on the unit strength, grout strength, type of mortar, length of curing, and the ratio of cross-sectional area of the units to the grout. The formula proved to be accurate for the test results obtained, as well as the results of several other researchers, but was based only on two-course high prisms constructed with masonry half-units. Prism strength was assumed to depend only on the curing time of the mortar and grout, as the concrete masonry units were considered to be old enough that their strength was effectively constant following grouting.

### 2.5.5 Modulus of Elasticity

Aside from the concentric axial compressive strength, another important property of masonry is the modulus of elasticity. The method allowed in CSA S304.1-04 uses the secant modulus calculated between 5% and 33% of the masonry compressive strength, and this has been suggested to relate directly to the prism strength by a single coefficient (Colville and Wolde-Tinsae, 1993). The modulus of elasticity for design purposes in CSA S304.1-04 is taken to be 850 times the masonry compressive strength, though values for the coefficient of 667, 750, and 900 have been proposed (Colville and Wolde-Tinsae, 1993; UBC, 2007; ACI 530.1-05, 2005, respectively).

Other research (Ameny et al., 1983) has suggested instead that the modulus should be determined based on an analysis of the elastic moduli of the constituent components instead of the compressive strength. This would include the elastic moduli of the grout, mortar, and masonry units in grouted masonry and would need to take into account any effects due to confinement, and is obviously a very complex approach.

Khalifa and Magzoub (1994) suggested that an estimate of $E_m$ as a linear value of $f'_m$ should not be the only formula, as $f'_m$ may be limited by bond strength between components rather than the strength of grout or block. A later investigation by Duncan (2008) compared standard grouted prisms to prisms with lubricated cores with the intention of isolating the effect of bonding between the grout and the masonry units. In this case, the compressive strength was statistically identical between well-bonded grout and grout with no bond, though the modulus of elasticity was significantly lower in prisms with no bonding. Subsequent tests by Duncan (2008) with other grout mixes suggested that the stiffness of the grout has more of an impact on prism strength and stiffness than the grout strength.

## 2.6 Prescribed Strength Values in the Canadian Standard

The current Canadian standard provides tabulated values for concrete masonry compressive strength based on the masonry components. Table 4 in CSA S304.1-04 bases the compressive strength normal to the bed joint as a function only of the unit compressive strength, whether masonry is grouted or hollow, and the mortar type. Factors that are not taken into consideration include the unit tensile strength and stiffness, the grout strength and stiffness, and the bond strength between the masonry units and the grout, all of which have been shown to be important factors in previous research.

Drysdale and Hamid (1979) suggested that basing $f'_m$ only on block strength and mortar type may not be appropriate for grouted concrete block masonry due to the minimal effect of the mortar joint on the compressive strength of the prism. They instead recommended an approach that takes into account the strength of the grout, the ratio of the grout strength to the strength of a similar but hollow prism, and the interaction between the grout and masonry units.

A database of the compressive strength of grouted concrete masonry prisms was constructed in order to assess the extent of conservatism in the prescribed $f'm$ values in the current Canadian Standard, CSA S304.1-04, and provide a background for developing a correlation between unit and prism strength. A total of 137 average compressive strength data points and corresponding specified strength values were computed from the results of 508 individual grouted concrete masonry prism tests. Prism strength computations were performed according to CSA S304.1-04, and a full list of the references used in this analysis is given in Appendix A.

The majority of the prism tests examined in this database were three units high, and ranged from a minimum of two units to a maximum of eight. The majority of masonry units were standard 190x190x390 mm stretcher units, with most of the remainder being 190x190x190 mm half-units. Masonry unit strength in the database ranged from 10.50 - 41.55 MPa, and grout strength in the database was limited to 10 – 42 MPa in order to stay within the range of observed unit strength values. Following the strength requirements of CSA A179, mortar with compressive strength of 5 – 12.5 MPa was classified as type N, and mortar with compressive strength of 12.5 – 17.6 MPa was classified as type S.

Appropriate correction factors were applied to the computed masonry strength values to take into account the influence of prism height to thickness ratios on prism strength. The values obtained directly from research were modified by the factors found in Table D.1 of the masonry design standard, CSA S304.1-04.

Tests from a total of 263 prisms constructed with type N mortar and 245 prisms constructed with type S mortar were analyzed. In order to be consistent with the methodology used by Maurenbrecher (1986) for the current values in Table 4, a bilinear best fit relationship was developed between the average unit strength and the average prism strength. The critical points of the bilinear relationship were chosen at unit strength values of 0, 20, and 40 MPa to cover the full range of CMU strengths in Table 4.

Figure 2-1 and Figure 2-2 represent the database results for type N and type S mortar, respectively. The results are plotted alongside the prescribed values in CSA S304.1-04 for comparison.

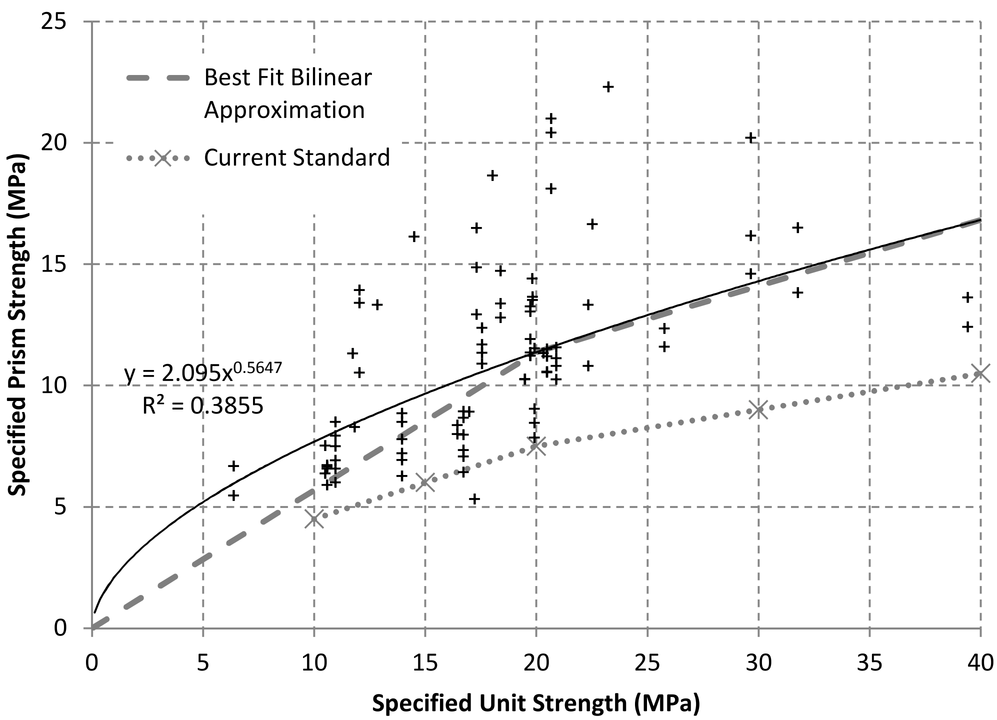



**Figure 2-1: Database Results for Prisms with Type N Mortar**

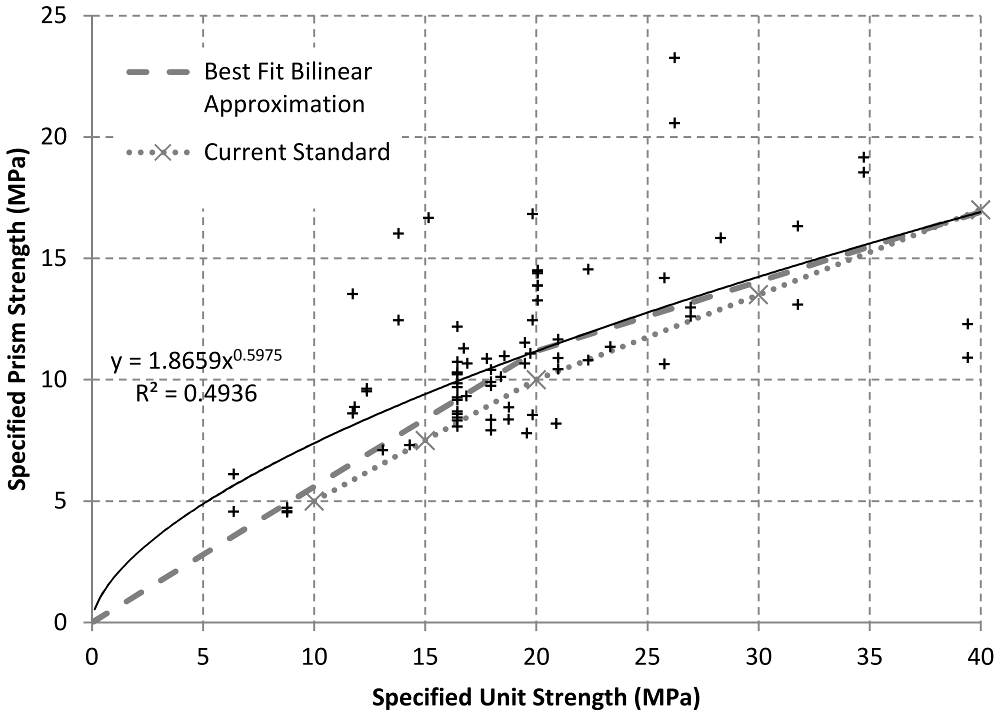



**Figure 2-2: Database Results for Prisms with Type S Mortar**

The results from both the type N and type S mortar database analyses indicate a large degree of scatter. This is likely due to differences in construction and testing procedures, grout strength and composition, and mortar strength that were not accounted for in the database. Both type N and type S mortar results had best fit curves in the form of a power relationship with the format $y = mx^b$, with exponents ranging from 0.56 – 0.60. This is similar in principle to the relationship between prism strength and unit strength proposed by the Australian masonry structure standard AS 3700-2011 (2011), which specifies a square root relationship between the two. The database results are summarized in Table 2-1, alongside the current tabulated values in CSA S304.1-04.

**Table 2-1: Database Analysis Summary**

| Unit Strength (MPa) | Type S Mortar | | | Type N Mortar | | |
|---|---|---|---|---|---|---|
| | S304 | Best Fit | Difference | S304 | Best Fit | Difference |
| 40 | 17 | 16.91 | -0.5% | 10.5 | 16.82 | +60.2% |
| 30 | 13.5 | 14.04 | +4.0% | 9 | 14.10 | +56.6% |
| 20 | 10 | 11.18 | +11.8% | 7.5 | 11.37 | +51.6% |
| 15 | 7.5 | 8.38 | +11.8% | 6 | 8.53 | +42.2% |
| 10 | 5 | 5.59 | +11.8% | 4.5 | 5.69 | +26.4% |

The results from the database analysis suggests significant conservatism in grouted concrete masonry prisms constructed with type N mortar on the order of 26 – 60%, and lesser conservatism for prisms constructed with type S mortar on the order of 4 - 12%, with no conservatism present at unit strength values of 40 MPa. Prisms constructed with type S mortar did not have a significant difference in strength from the prisms constructed with type N mortar, which is significantly less than the difference of 11-62% that is currently in S304.1-04.

The observed conservatism in the prescribed *f'm* values has led to a companion study in the United States by the National Concrete Masonry Association, also with the goal of recalibrating the unit strength design method (NCMA, 2012). The research performed by the NCMA suggested increases to the design standard based on tests of prisms constructed in idealized laboratory conditions, which may not necessarily be reflective of the variability inherent in field construction.

## 2.7 Predictive Formulas

Several researchers have attempted to develop formulas to predict the strength of prisms based on different properties of the constituent materials. In general, the formulas are expressed in terms of the concrete masonry unit strength ($f_b$), mortar strength ($f_m$), and grout strength ($f_c$).

Khalaf et al. (1994) tested a series of prisms with variations in material strength, and came up with a simple equation to predict grouted prism strength. The research maintained the standard 10 mm thick mortar joint between tests, and used masonry unit geometry similar to the units used in Canada, though it was 60% solid. The formula developed was a linear addition of material strengths, and is given in Equation 2.1. The strength values for mortar and grout were based on samples taken using non-absorbent moulds, and may not reflect the true in-situ strength of the materials. This formula may have limitations, as the authors themselves suggested that grouted prism strength is insensitive to changes in mortar strength once the mortar has surpassed 9.0 MPa, which is already close to the minimum value allowed for type S mortar.

$$f'_m = 0.30f_b + 0.20f_m + 0.25f_c \qquad \textbf{Eq. 2.1}$$

Later research by Thompson et al. (2002) attempted to include the effects of grout curing time on prism strength, and developed Equation 2 based on a database of prism test results. In Equation 2.2, $G$ is a grout strength coefficient, $U$ is a unit strength coefficient, and $D$ is the time in days since construction and pouring of the grout. The two material coefficients take into account the grout and unit strengths, the volume proportion between grout and masonry unit, and a newly developed moisture content factor for both the grout and masonry unit. A final factor for both coefficients was a construction factor – in the grout coefficient this was a factor based on the height-to-thickness correction factors in ASTM C 1314, and in the unit coefficient this was a factor accounting for the type of mortar used in construction, but was developed based in part on the current tabulated $f'_m$ values in the American code. The equation is therefore relatively complex, based in part on the American design code, and also based on a series of data covering a narrow scope of material strengths, only type S mortar, and only half-units.

$$f'_m = G\ln(D + 1) + U \qquad \textbf{Eq. 2.2}$$

## 2.8 Closure

Many of the requirements for prism testing and construction set out in CSA S304.1-04 already follow the best practices as established from past research. In order to obtain prism compressive strength results as similar as possible to those that would be observed in a similarly-constructed wall, three-course high prisms were chosen in this program in a running bond pattern. The discontinuities in the grout provided by the two half units in the center course are anticipated to provide a more realistic failure mechanism to that of a real fully-grouted wall constructed in a running bond.

As the focus of this research is to examine the prescribed $f'_m$ values of the Canadian masonry design standard, it is important that the construction of the masonry prisms follow standard Canadian construction practice as closely as possible. Although the strength of the mortar is anticipated to have a limited effect on the total prism strength, both type N and S mortars will be used in construction in order to capture data on all of the combinations covered under the current standard.

Much of the research performed on grouted masonry prisms is either out of date with current construction practices, does not follow procedures accepted in the Canadian standard, or does not cover the full range of material variability available to designers. The research presented in this thesis is intended to be comprehensive and provide a better understanding of the correlation between grouted masonry prism strength and the strength of its component materials for design and construction performed in Canada.

# CHAPTER THREE
# EXPERIMENTAL PROGRAM

The procedures used for constructing and testing the concrete masonry prisms and their constituent materials are presented in this chapter. Test procedures conformed with established CSA and ASTM standard requirements wherever possible.

## 3.1 Materials and Auxiliary Testing

### 3.1.1 Concrete Masonry Units

The concrete masonry units used were standard 190x190x390 mm stretcher type and 190x190x190 mm half units. Half units of 10 MPa strength were not available, so full units were cut into halves for prism construction. The units were supplied from a local masonry producer at requested strength values of 10, 15, 20, 30, and 40 MPa to replicate the values used in Table 4 of CSA S304.1-04. The masonry stretcher units were 56.0% solid, and the masonry half units were 64.0% solid (Expocrete, 2012).

The concrete masonry units were tested for the water absorption and compressive strength, and were measured in accordance with ASTM C140. The compressive strength was determined by sulphur capping five units of each unit strength, and testing them under axial compression in a universal 6600 kN MTS test machine. A specifically-designed mould with dimensions of 400x200 mm was manufactured for the sulphur capping to ensure a smooth surface and aid in masonry unit alignment during the capping process. The sulphur compound used for capping was a Forney Hi-Cap silica-filled, flake form compound, with a manufacturer-supplied strength of 62 MPa.

The water absorption was determined by submerging three units of each strength in water for 24 hours, and comparing their saturated mass to their oven-dry mass after being dried at 100$^{o}$C for a further 24 hours.

### 3.1.2 Mortar

Four types of mortar were used during construction. Type N and type S mortar were used, with mixes consisting of Masonry Cement (MC) and Portland Cement Lime (PCL) mortar. Mortar was mixed during prism construction to a flow determined to be suitable by the masons. The mortar was supplied in commercially-available packages that required the addition of water on-site. Six mortar samples were taken for each mix during prism construction as per CSA A179-04. Each sample was cast in a 50 mm plastic cubic mould, and de-moulded 24 hours after casting. The mortar samples were left to air cure alongside the prisms in the lab prior to compression testing. The mortar cubes were tested in accordance with ASTM C109 using a Forney FX 500 compression test machine at a minimum of 28 days following curing.

### 3.1.3 Grout

Coarse grout was mixed on site during prism construction for phases 1 and 3, but was provided pre-mixed for phase 2 construction. Six grout samples per mix were taken during construction using non-absorbent cylinder moulds measuring 100mm in diameter and 200mm high. Grout cylinders were sampled and moulded in accordance with CSA A179 throughout the grouting of the prisms, and left to cure for 28 days before being tested under compression.

Grout cores were cut from untested masonry prisms. Grout cores were cut to a size of 75mm by 75mm by 150 mm to follow the dimensions used in in-situ grout testing as suggested in ASTM C1019. These dimensions maintained the 2:1 height-to-thickness ratio similar to the grout cylinders. A study by Yi et al. (2006) found that the difference in apparent strength between a 100x200 mm cylinder and a 75x75x150 mm prismatic sample was less than 1% for identical concrete, suggesting that a direct comparison between the two is valid. All specimens were tested in a Forney FX 500 compression testing machine according to ASTM C39, and the samples were end-ground to provide plane loading surfaces. Figure 3-1 shows schematics for both grout cylinders and prismatic cores. A summary of the sampling and testing program is given in Table 3-1.

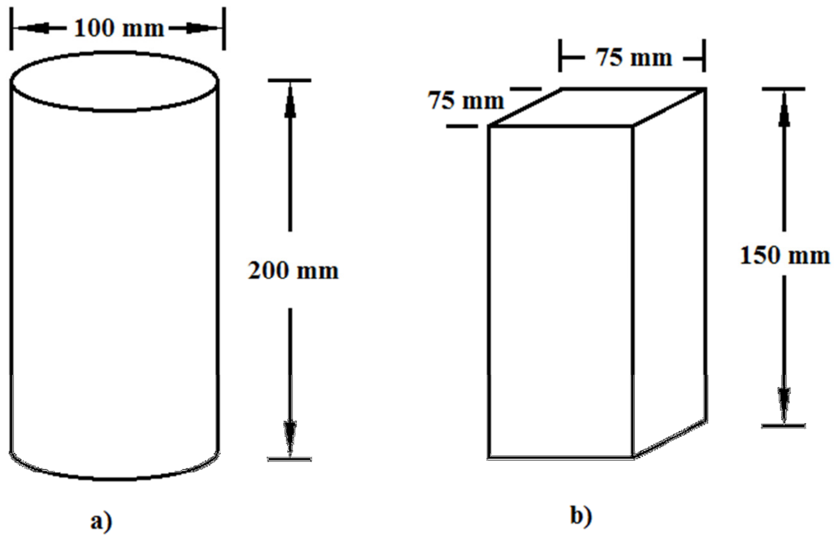



**Figure 3-1: Dimensions of the a) Grout Cylinder Specimens and b) Prismatic Grout Cores**

**Table 3-1: Summary of the Standards Used in the Test Program**

| Property | CMU Compressive Strength | CMU Absorption | Grout Compressive Strength | |
|---|---|---|---|---|
| | | | Non-Absorbent Moulds | In-Situ Prismatic Cores |
| **Sampling Method** | NA* | NA | CSA A179 | ASTM C1019 |
| **Test Method** | ASTM C140 | ASTM C140 | ASTM C39 | ASTM C39 |
| **No. of Specimens** | 5 | 3 | 6 | 5 |

*NA: not applicable

## 3.2 Prism Construction and Testing

Twenty grouted concrete masonry prism groups of seven prisms each were constructed for testing under axial compression. All prisms were three units high and built in a running bond pattern by professional masons as per Annex D of CSA S304.1-04. The second course consisted of two half-units with a head joint in between. Prisms were constructed using nominal 10, 15, 20, 30, and 40 MPa concrete masonry units with either type S or type N mortar. A summary of the experimental test program is given in Table 3-2. The group designation in Table 3-2 begins with the nominal unit strength followed by the mortar mix (PCL or MC) and type (N or S). For example, 40-PCL-S refers to a group of prisms constructed using 40 MPa units and PCL mix type S mortar.

Due to space limitations, the construction and testing of the prisms was conducted in three distinct phases, with each phase using different masons. Phases 1 and 2 each comprised half of the prisms constructed with the nominal 20 MPa, 30 MPa, and 40 MPa concrete masonry units, where Phase 1 used PCL-N and MC-S mortars and Phase 2 used PCL-S and MC-N mortars. Phase 3 consisted of all prisms constructed with 10 MPa and 15 MPa nominal concrete masonry units, and included all mortar type combinations. Figure 3-2 shows prisms from Phase 3 immediately following construction. As a result of the phase structure, multiple batches were developed for both mortar and grout. The designation in the grout mix column of Table 3-2 indicates the phase in which the prism group was constructed, and subsequently the grout mix and strength used.

**Figure 3-2: Phase Three Prisms after Construction**

Prisms were left to cure in the ambient laboratory conditions, which were temperature controlled by not humidity controlled. All prisms were capped using Hydrostone plaster conforming to ASTM C1552 (2009). Prior to testing, two half-inch thick fibreboard planks (13x190x390 mm) were placed along the prism top and bottom to further reduce the confinement effect of the machine heads. The compression tests were carried out according to CSA S304.1-04 Appendix D using a Universal 6600 kN MTS test machine with a set-up as shown in Figure 3-3. The upper and lower machine heads were 610 mm in diameter with a spherically-seated and hardened upper platen. Axial strains were measured with four 400mm long LVDTs that were mounted onto the outside of each prism.

**Table 3-2: Summary of the Test Program**

| Group Designation | Nominal CMU Strength (MPa) | Mortar Type and Mix | | Grout Mix | Prism Height and Construction | No. of Prisms |
|---|---|---|---|---|---|---|
| | | Type S | Type N | | | |
| 40-PCL-S | 40 | PCL | - | G2 | three units running bond | 5 |
| 40-PCL-N | | - | PCL | G1 | | 5 |
| 40-MC-S | | MC | - | G1 | | 5 |
| 40-MC-N | | - | MC | G2 | | 5 |
| 30-PCL-S | 30 | PCL | - | G2 | three units running bond | 5 |
| 30-PCL-N | | - | PCL | G1 | | 5 |
| 30-MC-S | | MC | - | G1 | | 5 |
| 30-MC-N | | - | MC | G2 | | 5 |
| 20-PCL-S | 20 | PCL | - | G2 | three units running bond | 5 |
| 20-PCL-N | | - | PCL | G1 | | 5 |
| 20-MC-S | | MC | - | G1 | | 5 |
| 20-MC-N | | - | MC | G2 | | 5 |
| 15-PCL-S | 15 | PCL | - | G3 | three units running bond | 5 |
| 15-PCL-N | | - | PCL | G3 | | 5 |
| 15-MC-S | | MC | - | G3 | | 5 |
| 15-MC-N | | - | MC | G3 | | 5 |
| 10-PCL-S | 10 | PCL | - | G3 | three units running bond | 5 |
| 10-PCL-N | | - | PCL | G3 | | 5 |
| 10-MC-S | | MC | - | G3 | | 5 |
| 10-MC-N | | - | MC | G3 | | 5 |

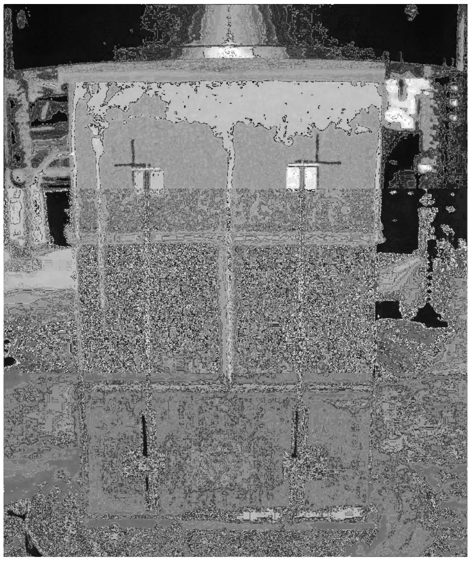


**Figure 3-3: Prism Test Set-Up**

# CHAPTER FOUR
# RESULTS AND DISCUSSION

In this chapter, the results of the auxiliary testing of the units, mortar, and grout, and the results of the grouted masonry prisms are presented and discussed. Only average and specified values are presented and discussed in this chapter. For the results of individual specimens, the reader is referred to Appendices B and C at the end of the thesis.

## 4.1 Results of the Auxiliary Testing

### 4.1.1 Concrete Masonry Units (CMU)

Concrete masonry units were tested both under axial compression and for water absorption. A summary of the test results is presented in Table 4-1. Compressive strength values were computed from testing five units, and each average water absorption value was determined from the results of three identical units. The range of water absorption values was similar to that of previous research (Hedstrom and Hogan, 1990), and with the exception of the nominal 15 MPa units, the results satisfy the maximum water absorption requirements of CSA A165.

**Table 4-1: Test Results for Concrete Masonry Units**

| Nominal Unit Strength (MPa) | 24 hour Water Absorption (%) | | Compressive Strength (MPa) | | |
|---|---|---|---|---|---|
| | Average | COV (%) | Average | COV (%) | Specified |
| 10 | 10.17 | 2.21 | 7.61 | 3.45 | 6.37 |
| 15 | 14.11 | 1.06 | 26.71 | 3.13 | 22.33 |
| 20 | 10.59 | 2.70 | 33.00 | 13.38 | 25.76 |
| 30 | 7.95 | 5.82 | 47.13 | 2.15 | 39.40 |
| 40 | 5.76 | 7.33 | 61.42 | 7.57 | 51.35 |

With the exception of the nominal 10 MPa units, the specified strengths of the units were significantly higher than the nominal strengths quoted by the supplier. The nominal 10 MPa units needed to be specially mixed as they are not commonly used in construction, and used a distinct aggregate mix, which may have led to a specified strength lower than nominal. The remaining CMUs demonstrated significantly stronger compressive strength than their nominal values, likely due to precautions taken by the supplier during the concrete mixing to ensure meeting or exceeding the target strength. A comparison of the nominal 15 and 20 MPa concrete masonry units shows a similar specified strength was obtained for the two unit strengths, however a single variable ANOVA analysis suggests that the two unit strengths are still statistically significantly different.

Strain measurements were also taken during the CMU compressive strength tests in order to determine the Young's Modulus of the units. The results are presented in Table 4-2, and graphically in Figure 4-1. The results presented in Figure 4-1 demonstrate a strong linear correlation between the strength and the modulus of elasticity of the concrete masonry units.

**Table 4-2: Modulus of Elasticity Results from CMU Testing**

| Nominal Unit Strength (MPa) | Specified Unit Strength (MPa) | Young's Modulus (MPa) | Young's Modulus COV (%) |
|---|---|---|---|
| 10 | 6.37 | 932.59 | 17.82 |
| 15 | 22.33 | 3311.92 | 13.40 |
| 20 | 25.76 | 3707.59 | 4.82 |
| 30 | 39.40 | 5190.72 | 1.34 |
| 40 | 51.35 | 6198.34 | 3.82 |

Figure 4-2 demonstrates the relationship between the 24 hour water absorption of the concrete masonry units and their specified compressive strength values. The results are plotted excluding the results from the nominal 10 MPa units, as they were cast using a different aggregate mixture than the other units.

A strong correlation was found between the 24 hour water absorption values and the specified compressive strength of the masonry units as shown in Figure 4-2. The results demonstrate a strong trend where increased unit strength correlates with lower water absorption. This is anticipated as higher strength units tend to require a higher cement content, and greater compaction during manufacturing, for the same aggregate type. Together, these factors typically result in lower porosity and lower total absorption (Drysdale and Hamid, 2005).

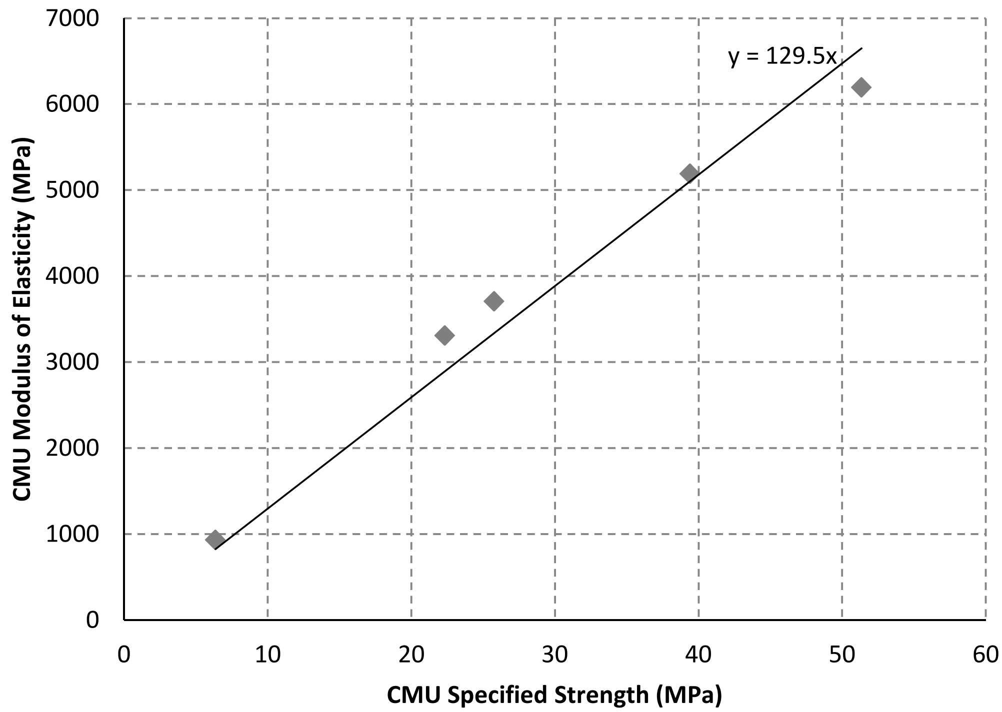



**Figure 4-1: CMU Modulus of Elasticity as a Function of Compressive Strength**

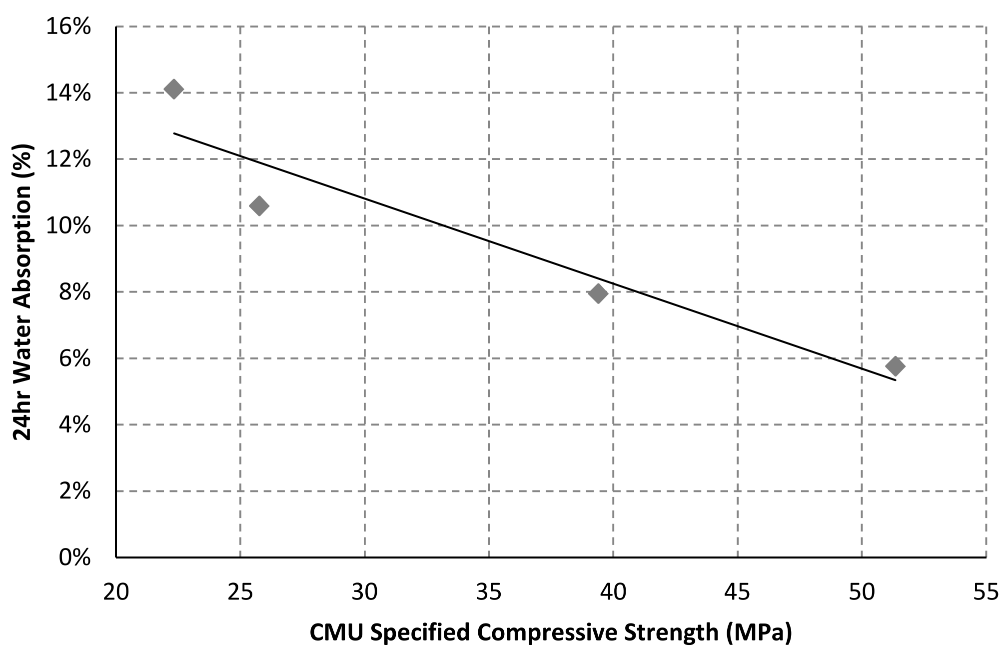



**Figure 4-2: Water Absorption versus CMU Compressive Strength**

### 4.1.2 Mortar

The results from the mortar compression tests are summarized in Table 4-3. There was significant variation in the mortar strengths used in prism construction. As each phase was constructed by different masons, this variation was likely due to differences in the amount of mix water used and preparation preferences between the masons. Type N mortar strengths ranged from 3.85-10.98 MPa, and type S mortar ranged from 13.63-22.81 MPa.

Mortar compressive strength values meet the requirements of CSA A179 for minimum mortar cube strength for job-prepared mortar mixes. Examining the four mixes for each mortar type, there was no consistent strength difference between PCL and MC mortar.

**Table 4-3: Mortar Compressive Strength Test Results**

| Construction Phase | Mortar Type | Average Strength (MPa) | COV (%) |
|---|---|---|---|
| 1 | MC-S | 17.43 | 10.52 |
| | PCL-N | 10.98 | 14.01 |
| 2 | MC-N | 9.01 | 10.47 |
| | PCL-S | 22.81 | 4.80 |
| 3 | MC-N | 3.85 | 2.76 |
| | MC-S | 13.63 | 10.67 |
| | PCL-N | 7.06 | 13.70 |
| | PCL-S | 15.05 | 7.92 |

### 4.1.3 Grout

A summary of the compressive strength test results for grout cast in non-absorbent cylinders is given in Table 4-4. As the construction of the prisms in phase 1 was performed over a span of two days, and the grouting process was not continuous during construction, a total of 18 samples were tested for grout cast in phase 1. Six grout samples were tested for prisms constructed during phases 2 and 3 as the grouting was performed continuously during a shorter time span.

**Table 4-4: Test Results for Grout Specimens Cast in Non-Absorbent Cylinders**

| Grout Designation | Construction Phase | Compressive Strength (MPa) | | Slump (mm) |
|---|---|---|---|---|
| | | Average | COV (%) | |
| G1 | 1 | 28.23 | 9.42 | 160 |
| G2 | 2 | 10.60 | 4.54 | 220 |
| G3 | 3 | 22.16 | 6.56 | 170 |

A single-variable ANOVA analysis was performed on the grout samples taken during Phase 1 construction and showed no statistical difference between the samples taken on either day of testing. As a result the full data set was combined and is presented as a single value in Table 4-4. CSA S304.1-04 indicates that designers should expect 28 day minimum grout strengths of 10 to 12 MPa for fine and coarse grout, respectively, and that such strengths lead to a satisfactory structural performance. As coarse grout was used for all three mixes, grout mixes G1 and G3 meet the minimum requirements for compressive strength, however mix G2 does not.

Grout strength tests were also performed to determine the strength of prismatic grout cores removed from untested prisms and the results are presented in Table 4-5. The grout strength ratio reported in Table 4-5 was computed as the average compressive strength of five prismatic grout cores divided by the average compressive strength of grout cylinders.

**Table 4-5: Compressive Strength of Grout Cores Removed from Untested Prisms**

| Nominal Unit Strength (MPa) | Construction Phase | Compressive Strength (MPa) | COV (%) | Strength Ratio |
|---|---|---|---|---|
| 20 | 1 | 32.77 | 8.08 | 1.16 |
| 30 | | 29.50 | 14.39 | 1.05 |
| 40 | | 25.22 | 3.38 | 0.89 |
| 20 | 2 | 16.31 | 13.37 | 1.54 |
| 30 | | 17.27 | 7.30 | 1.63 |
| 40 | | 15.18 | 6.36 | 1.43 |
| 10 | 3 | 32.41 | 4.50 | 1.46 |
| 15 | | 37.18 | 5.27 | 1.68 |

The strength ratios for grout cores taken from untested masonry prisms constructed in phases 2 and 3 are plotted in Figure 4-3 and Figure 4-4, against unit water absorption and compressive strength, respectively. Due to the inverse relationship between absorption and strength as shown in Figure 4-2, it is not surprising that Figure 4-3 and Figure 4-4 demonstrate opposing correlations.

The grout used in phase 1 demonstrated a significantly lower grout strength increase ratio than the grout from phases 2 and 3, and the specimens removed from the nominal 40 MPa even showed a decrease. This is potentially the result of the relatively lower slump, and therefore lower water content, for the phase 1 grout. As a result, the samples taken in non-absorbent moulds demonstrated significantly higher compressive strength than the grout from the other phases as there was hardly any free water for the masonry units to absorb. Another possibility is that the units used in the construction of phase 1 had much higher water content than those used in phases 2 and 3.

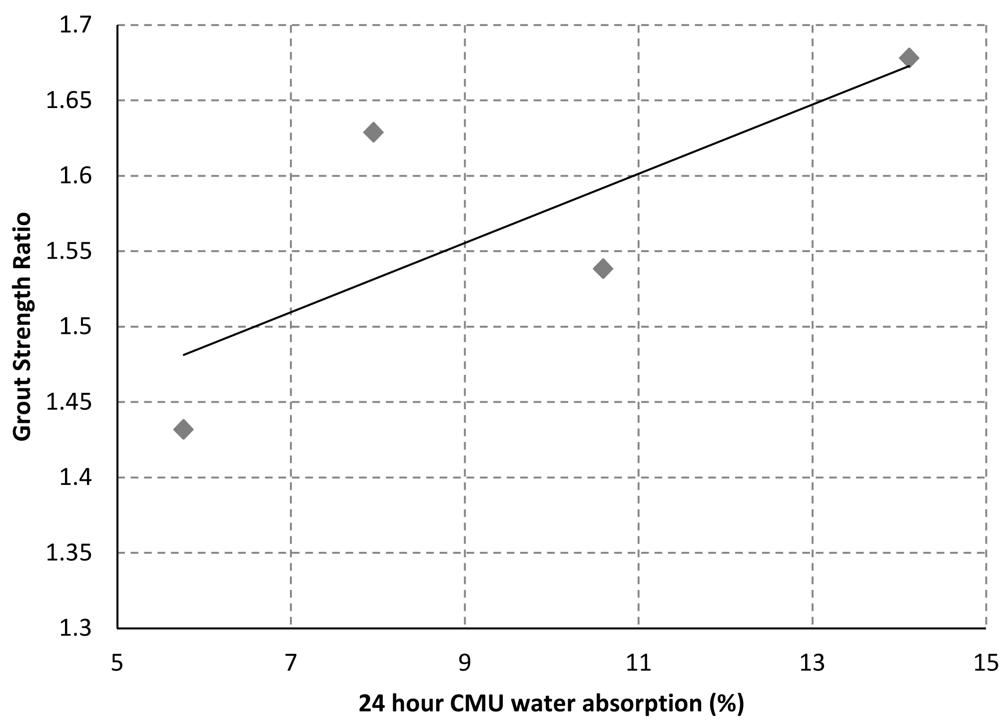



**Figure 4-3: Grout Strength Ratio versus CMU Water Absorption**

For the remaining phases of construction, grout specimens taken from untested masonry prisms show an increase in the in-situ grout strength to non-absorbent moulded sample strength ratio with increasing the concrete masonry unit water absorption. The majority of data points were above the presumed ratio of 1.5, and the grout strength ratio ranges from 1.4 to 1.7. These results fall within the range of results from previous researchers (Ocean Technical Report, 1975; Drysdale and Hamid, 1979; Bexton and Tedos, 1989; Sturgeon et al., 1989).

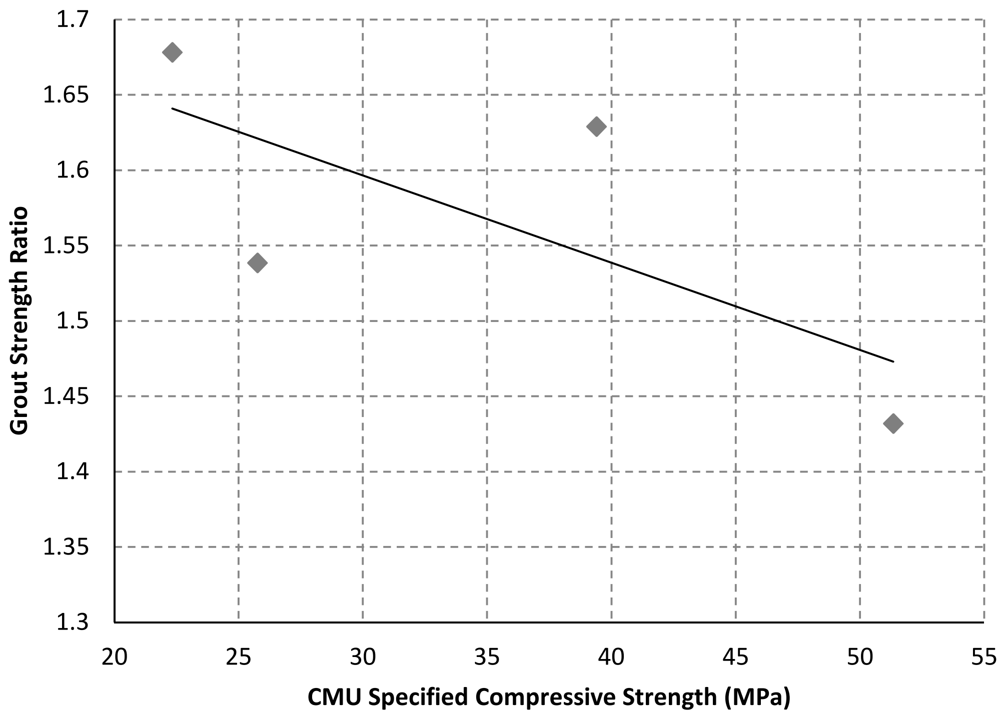



**Figure 4-4: Grout Strength Ratio versus CMU Compressive Strength**

## 4.2 Results of the Grouted Prisms

The results for grouted concrete masonry prisms tested under axial compression are presented in this section. Recorded maximum loads were divided by the gross cross-sectional area of the prisms, which was computed as 74,100 $mm^2$. As per Table D.1 of CSA S304.1-04, the compressive strength results were reduced by a factor of 0.9 to account for the height-to-thickness ratio of the prisms. The modulus of elasticity of the prisms was determined following the procedure outlined in Annex D of CSA S304.1-04, which specifies the use of a secant modulus over a stress range extending from 0.05 to 0.33 of the prism compressive strength. In the stress-strain figures presented in this section, the 0.9 factor was not applied to the stress values, and therefore higher maximum stress values are shown than the corresponding tabulated values.

### 4.2.1 Nominal 10 MPa Unit Prism Groups

The compressive strength and the modulus of elasticity results for prisms constructed with nominal 10 MPa units are presented in Table 4-6. The results for the 10-PCL-N series of prisms resulted in a coefficient of variation greater than 15%, and as a result additional prisms were tested.

Comparing the results of Table 4-6 with the mortar strength values from Table 4-3 suggests that an increase in mortar strength consistently resulted in a decrease in prism strength. This is likely due to deformational incompatibility between the relatively weak unit and the relatively stronger mortar; the mortar in the 10-PCL-S prisms had twice the compressive strength as the masonry units and resulted in a low failure load, while the mortar in the 10-PCL-N prisms had nearly the same compressive strength as the units, and the prisms were significantly stronger.

**Table 4-6: Strength and Modulus Results for the 10 MPa Series of Prisms**

| Prism Group | Grout | Mortar | Compressive Strength | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|---|
| | In-Situ Strength (MPa) | Average (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Average (GPa) | COV (%) | E/f'm |
| 10-MC-N | 32.41 | 3.85 | 7.98 | 8.10 | 6.67 | 18.52 | 14.35 | 2775 |
| 10-MC-S | | 13.63 | 7.31 | 7.36 | 6.11 | 17.33 | 18.82 | 2836 |
| 10-PCL-N | | 7.06 | 7.45 | 16.26 | 5.46 | 17.12 | 27.35 | 3134 |
| 10-PCL-S | | 15.05 | 5.52 | 10.48 | 4.57 | 12.92 | 26.47 | 2824 |

Stress-strain curves for the prisms constructed with 10 MPa units are plotted in Figure 4-5. Each curve represents the average stress-strain relationship for one group of prisms. The results are plotted up to the average maximum stress of the group of prisms, and full stress-strain curve results are given in Appendix C.

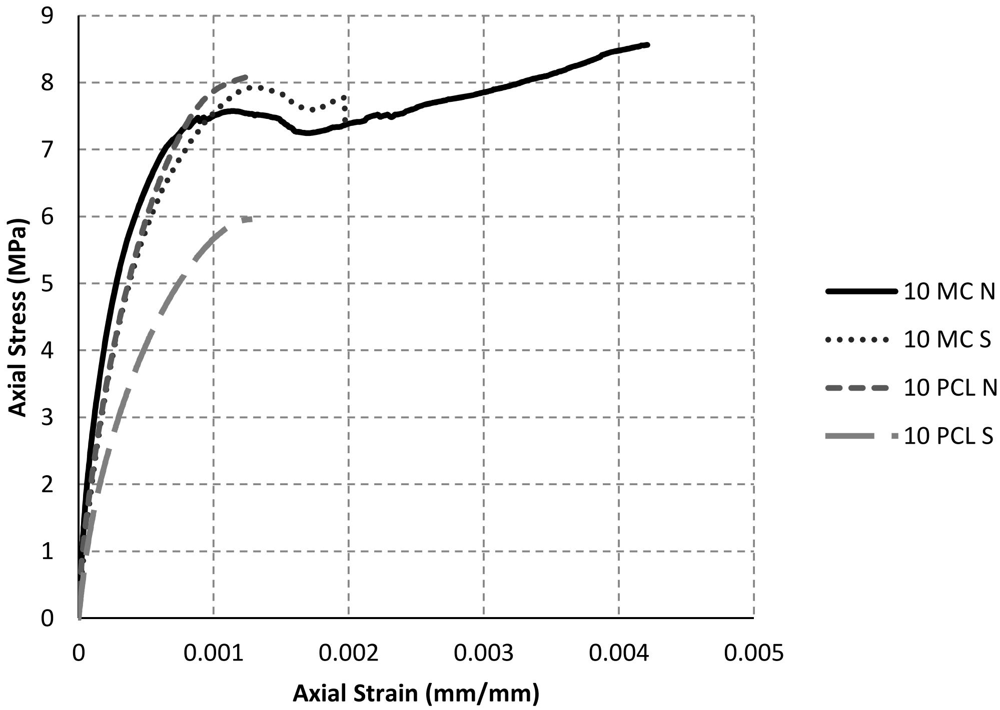



**Figure 4-5: Average Compressive Stress-Strain Curves for 10 MPa Unit Prisms**

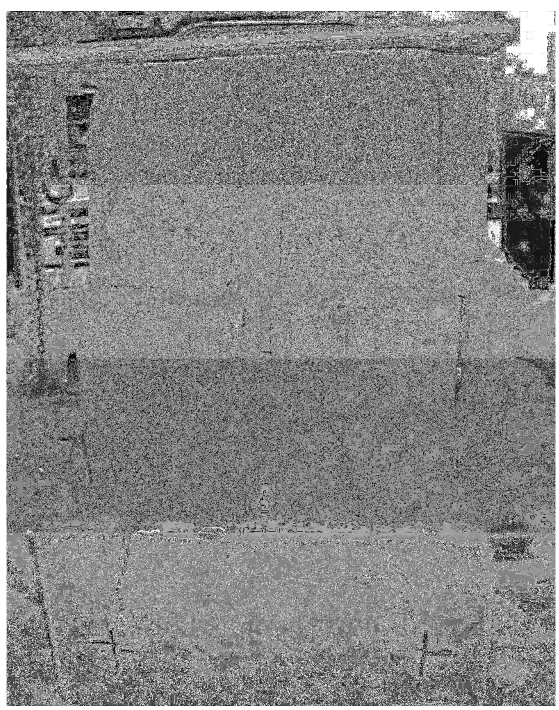


**Figure 4-6: Typical Failure Pattern for 10 MPa Unit Prisms**

The failure of the 10 MPa series of prisms demonstrated distinct phases, particularly the prisms constructed with MC mortars. A typical failure mode for this series of prism groups is shown in Figure 4-6. As the prism approached its maximum strength, the face shells of the masonry units broke and fell away from the grout cores, which then took on increased load until failure. As a result, one or both of the grout cores often remained intact following the collapse of the masonry unit face shells. Applying further loading to the remaining prism caused total failure of the grout cores at a second peak value in axial stress.

### 4.2.2 Nominal 15 MPa Unit Prism Groups

The results from the compressive testing of prisms constructed with nominal 15 MPa concrete masonry units are given in Table 4-7. The average stress-strain plots for each series of prisms are shown in Figure 4-7. Unlike the results from the tests on prisms constructed with nominal 10 MPa units, there was no significant variation in prism strength with changing mortar strength.

**Table 4-7: Strength and Modulus Results for the 15 MPa Series of Prisms**

| Prism Group | Grout | Mortar | Compressive Strength | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|---|
| | In-Situ Strength (MPa) | Average (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Average (GPa) | COV (%) | E/f'm |
| 15-MC-N | 37.18 | 3.85 | 15.93 | 5.62 | 13.32 | 23.75 | 11.42 | 1783 |
| 15-MC-S | | 13.63 | 17.40 | 3.46 | 14.54 | 24.65 | 4.30 | 1695 |
| 15-PCL-N | | 7.06 | 12.92 | 8.99 | 10.80 | 20.72 | 9.11 | 1919 |
| 15-PCL-S | | 15.05 | 13.96 | 13.79 | 10.80 | 23.69 | 13.74 | 2193 |

Figure **4-8** demonstrates a common failure pattern for prisms constructed with nominal 15 MPa units. The majority of prisms failed by spalling of the outer webs of the masonry units, followed by extensive cracking throughout the face shells. The grout cores nearest the location of the web spalling were typically damaged.

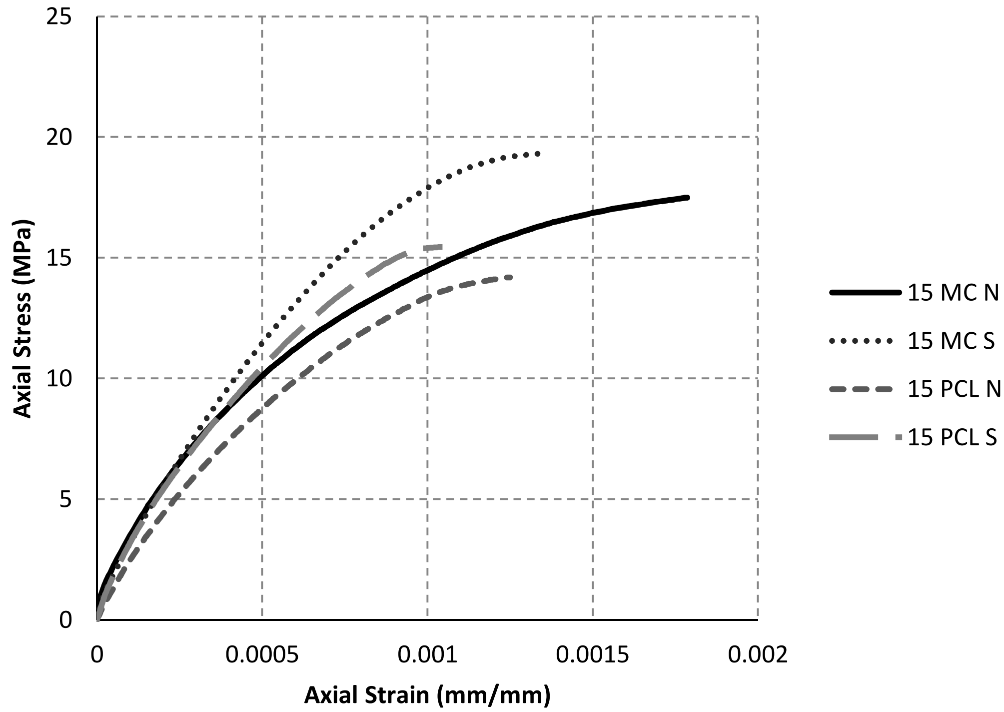



**Figure 4-7: Average Compressive Stress-Strain Curves for 15 MPa Unit Prisms**

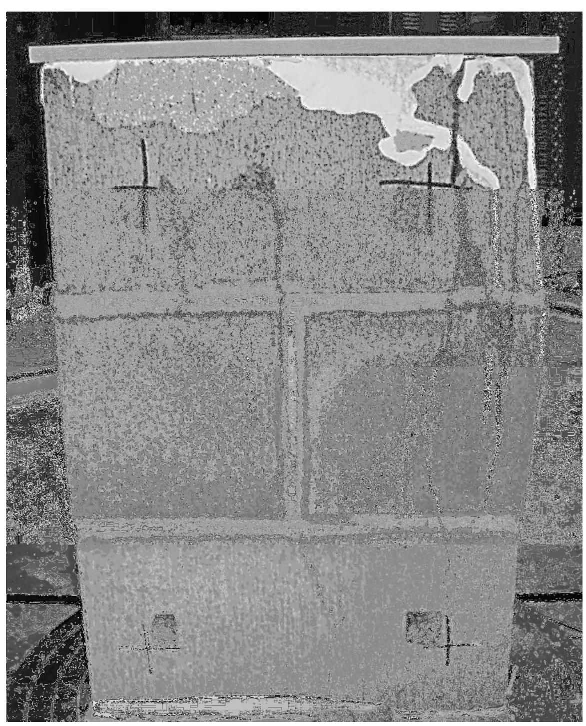


**Figure 4-8: Typical Failure Pattern for 15 MPa Unit Prisms**

### 4.2.3 Nominal 20 MPa Unit Prism Groups

Table 4-8 displays the results from the compressive testing of prisms constructed with nominal 20 MPa concrete masonry units. The average stress-strain plots for each series of prisms are presented in Figure 4-9.

**Table 4-8: Strength and Modulus Results for the 20 MPa Series of Prisms**

| Prism Group | Grout | Mortar | Compressive Strength | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|---|
| | In-Situ Strength (MPa) | Average (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Average (GPa) | COV (%) | E/f'm |
| 20-MC-N | 16.31 | 9.01 | 14.76 | 9.02 | 12.34 | 17.00 | 8.54 | 1377 |
| 20-MC-S | 32.77 | 17.43 | 12.74 | 3.76 | 10.65 | 21.63 | 19.07 | 2032 |
| 20-PCL-N | 32.77 | 10.98 | 13.88 | 8.08 | 11.60 | 17.36 | 4.42 | 1496 |
| 20-PCL-S | 16.31 | 22.81 | 16.98 | 5.43 | 14.19 | 25.19 | 2.64 | 1775 |

Figure 4-10 demonstrates a common failure pattern for the prisms constructed with nominal 20 MPa units and G1 grout. The majority of the prisms in this group failed by vertical splitting in the outer webs due to the expansion of the grout, frequently with minimal damage to the grout cores. There was often minimal damage to the face shells of the masonry units. The failure pattern observed for prisms constructed with type G2 grout (16.3 Mpa, weaker than G1 at 32.8 MPa) commonly demonstrated more separation of the masonry unit face shells from the grout, as shown in Figure 4-11. This is likely due to the similarity between the grout and unit strength – the average compressive strength of the masonry units was nearly identical to the in-situ grout strength for G1 grout, but twice the in-situ strength for the G2 grout.

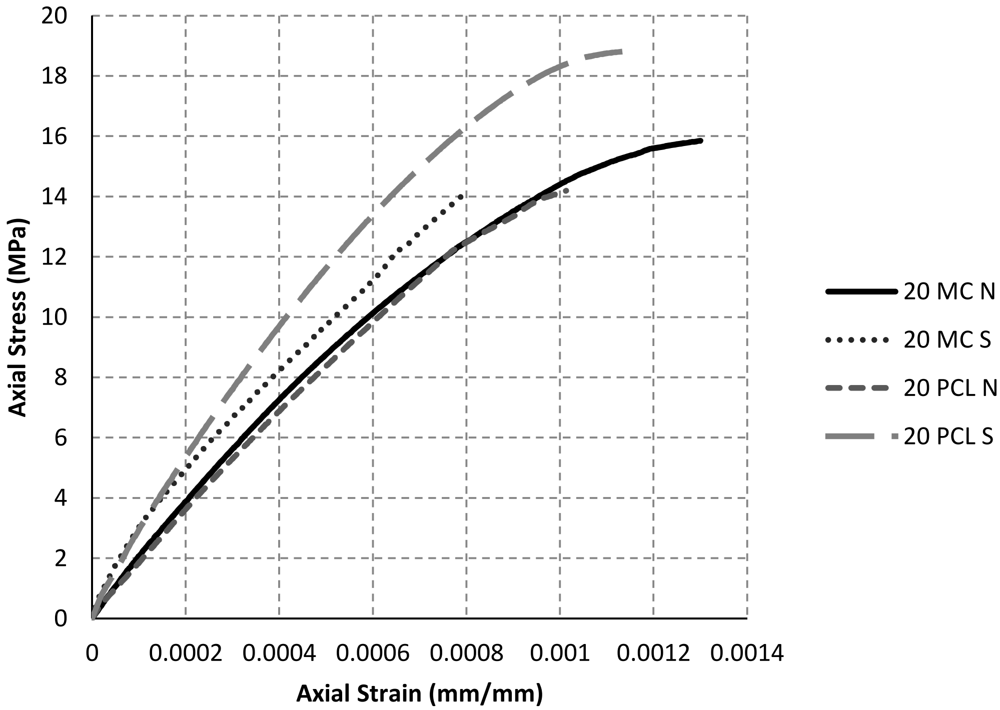



**Figure 4-9: Average Compressive Stress-Strain Curves for Prisms with 20 MPa Units**

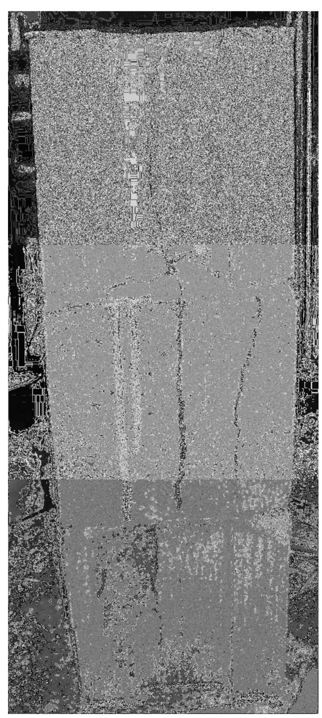


**Figure 4-10: Typical Failure Pattern for 20 MPa Unit Prisms with G1 Grout (32.8 MPa)**

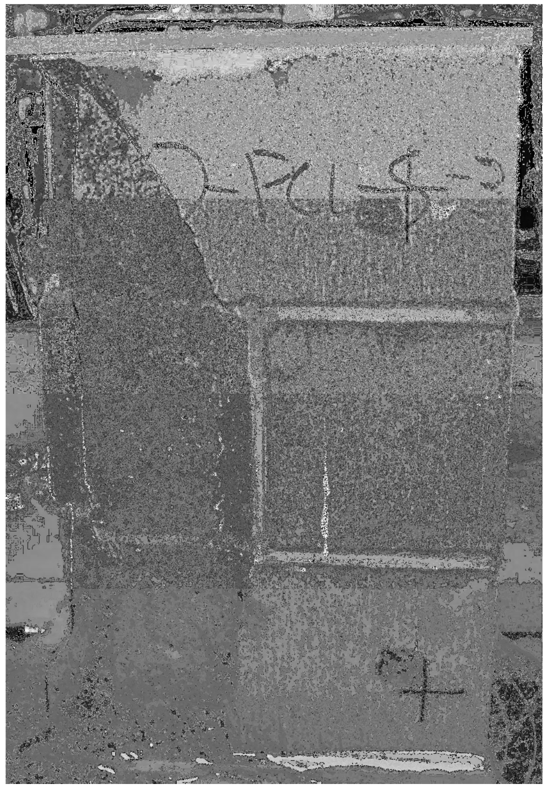


**Figure 4-11: Typical Failure Pattern for 20 MPa Unit Prisms and G2 Grout (16.3 MPa)**

### 4.2.4 Nominal 30 MPa Unit Prism Groups

Table 4-9 summarizes the results from the compressive testing of prisms constructed with nominal 30 MPa concrete masonry units. The average stress-strain plots for each series of prisms are presented in Figure 4-12.

**Table 4-9: Strength and Modulus Results for the 30 MPa Series of Prisms**

| Prism Group | Grout | Mortar | Compressive Strength | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|---|
| | In-Situ Strength (MPa) | Average (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Average (GPa) | COV (%) | E/f'm |
| 30-MC-N | 17.27 | 9.01 | 14.85 | 2.23 | 12.42 | 22.24 | 9.55 | 1791 |
| 30-MC-S | 27.73 | 17.43 | 13.05 | 5.72 | 10.91 | 23.40 | 7.58 | 2145 |
| 30-PCL-N | 27.73 | 10.98 | 16.52 | 10.66 | 13.63 | 21.71 | 11.75 | 1593 |
| 30-PCL-S | 17.27 | 22.81 | 16.02 | 14.2 | 12.29 | 34.71 | 13.11 | 2824 |

Figure 4-13 demonstrates the common failure pattern for this group of prisms. The prisms failed by extensive vertical cracking throughout the entirety of the masonry units, beginning with vertical cracking in the webs. There was no significant variation in failure behavior between the two grout mixes used for this unit strength. As well, the prism strength appeared to be insensitive to the strength of the mortar used. Both of these are likely due to the fact that the strengths of the grout mixes and the mortars are significantly lower than the strength of the masonry units used.

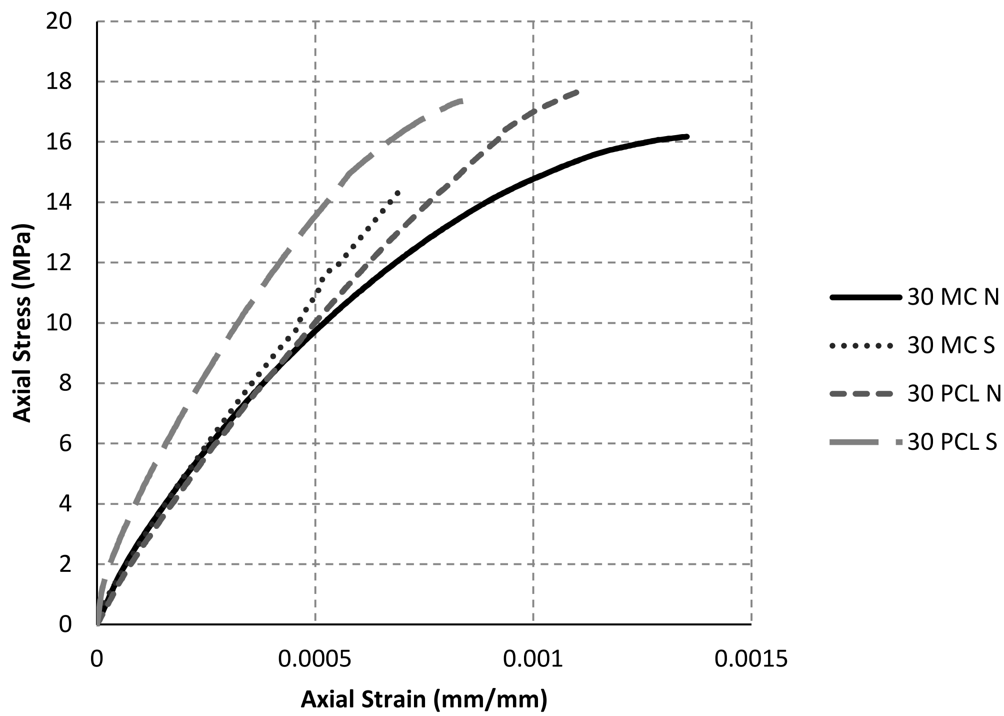
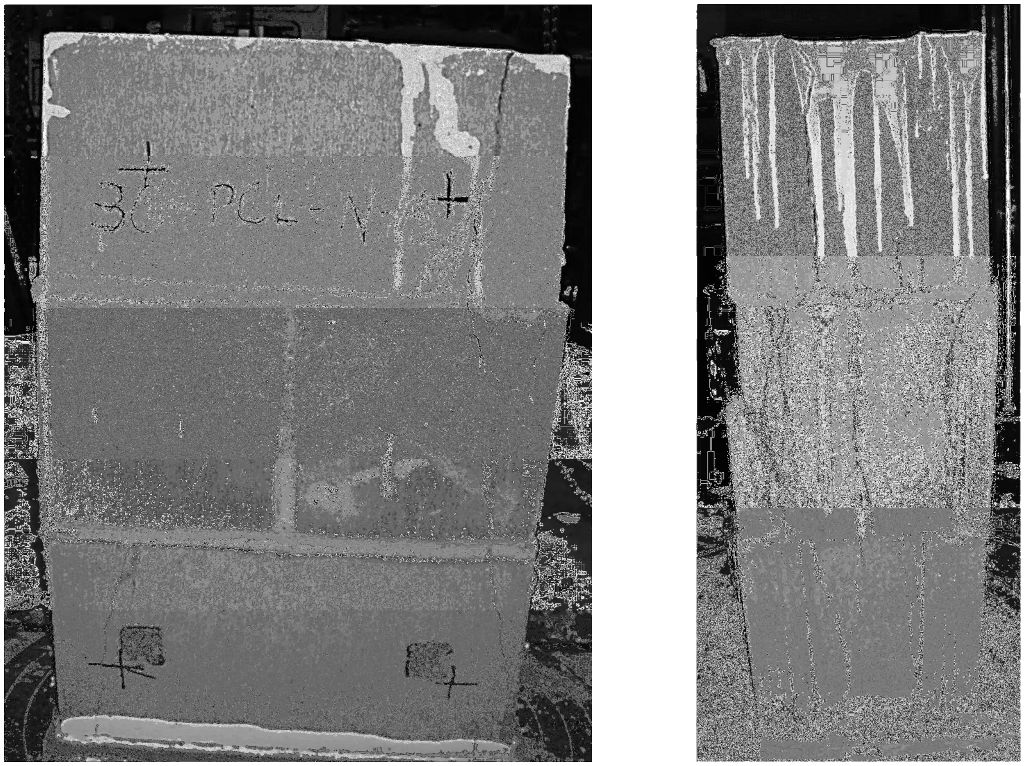



**Figure 4-12: Average Compressive Stress-Strain Curves for 30 MPa Unit Prisms**



**a) Elevation View** **b) Side View**

**Figure 4-13: Typical Failure Pattern for 30 MPa Unit Prisms**

### 4.2.5 Nominal 40 MPa Unit Prism Groups

The results from the compressive testing of prisms constructed with nominal 40 MPa concrete masonry units are given in Table 4-10. The average stress-strain plots for each series of prisms are presented as Figure 4-14.

**Table 4-10: Strength and Modulus Results for the 40 MPa Series of Prisms**

| Prism Group | Grout | Mortar | Compressive Strength | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|---|
| | In-Situ Strength (MPa) | Average (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Average (GPa) | COV (%) | E/f'm |
| 40-MC-N | 15.18 | 9.01 | 13.66 | 8.40 | 11.42 | 23.27 | 8.33 | 2037 |
| 40-MC-S | 25.22 | 17.43 | 19.17 | 10.43 | 15.89 | 29.64 | 8.60 | 1865 |
| 40-PCL-N | 25.22 | 10.98 | 19.15 | 8.07 | 16.01 | 24.62 | 10.32 | 1538 |
| 40-PCL-S | 15.18 | 22.81 | 17.58 | 5.24 | 14.70 | 31.36 | 6.13 | 2134 |

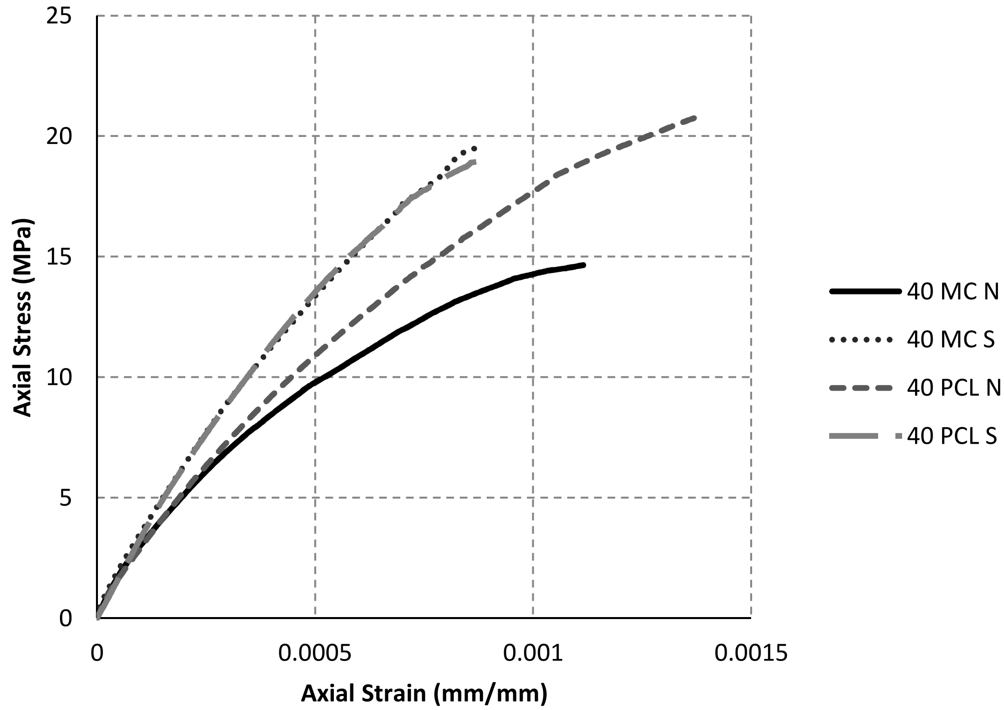
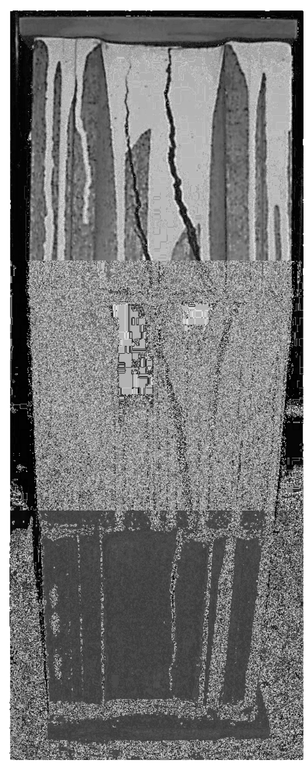



**Figure 4-14: Average Compressive Stress-Strain Curves for 40 MPa Unit Prisms**

**a) Elevation View**



**b) Side View**

**Figure 4-15: Common Failure Pattern for 40 MPa Unit Prisms**

Figure 4-15 demonstrates the common failure pattern for prisms constructed with nominal 40 MPa units. There was no significant difference in failure pattern between the two grout mixes used. Failure started with extensive vertical cracking in the outer unit webs, followed by vertical cracking throughout the face shells of the units.

### 4.2.7 Modulus of Elasticity

The individual Young's Modulus data points per prism are plotted in Figure 4-16 along with the formula specified in CSA S304.1-04. The points consistently fall above the values given by the current linear relationship.

Colville and Wolde-Tinsae (1993), among others, suggested that the Young's modulus of concrete masonry prisms is related to the prism strength by a linear factor. This suggests the possibility of an alternative format to present the Young's Modulus as presented in Figure 4-17, where the ratio between Young's modulus and prism strength is compared to the prism strength.

The elastic modulus results as presented in this format suggest that a higher order relationship is better suited to represent the result obtained, as the ratio between the modulus and prism strength itself may be dependent on the prism strength.

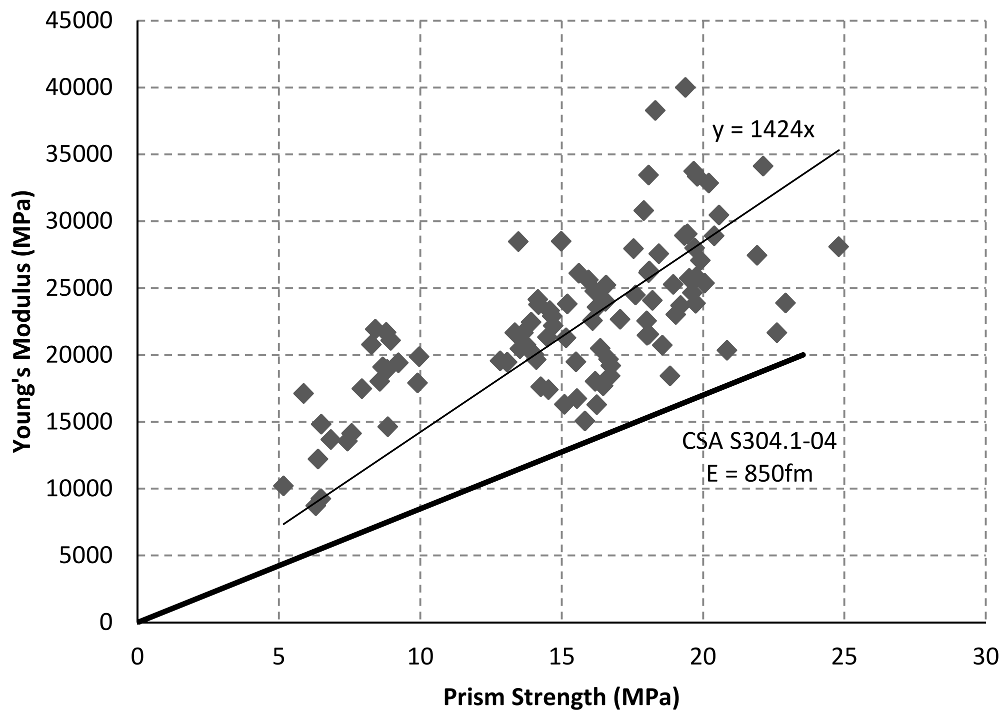



**Figure 4-16: Prism Elastic Modulus as a Function of Strength**

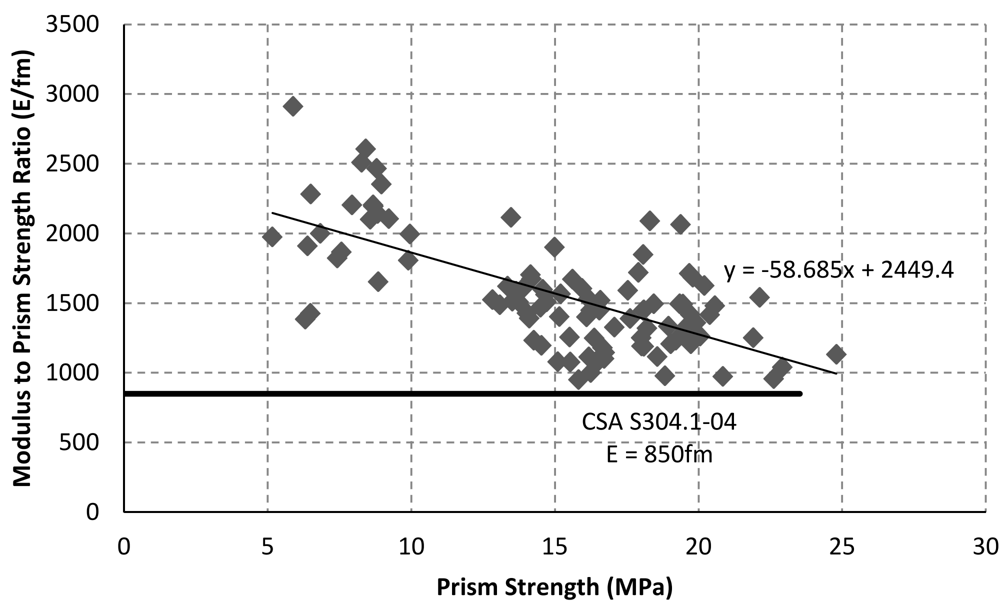



**Figure 4-17: Modulus to Prism Strength Ratio as a Function of Prism Strength**

The stiffness results from the prisms were consistently higher than the stiffness values suggested by CSA S304.1-04, with greater deviation from the standard occurring at lower values of unit strength, as shown in Figure 4-17.

Correspondingly, the vast majority of prisms failed at strain levels of approximately 0.001 mm/mm, which is considerably lower than the 0.002 mm/mm value suggested by Hamid and Drysdale (2005). As grout strength and stiffness are strongly correlated, it is likely that the relatively strong grout (between 1 and 3 times the recommended strength) is responsible for this increase in stiffness, as suggested by Duncan (2008).

## 4.3 Prism Test Summary and Discussion

A summary of the prism test results is presented in Table 4-11, and the results are plotted in Figure 4-18 and Figure 4-19 for type N and type S mortar, respectively.

**Table 4-11: Prism Compressive Strength Test Summary**

| Group | Spec. CMU (MPa) | In-situ Grout (MPa) | Mortar Strength (MPa) | | Prism Strength (MPa) | | |
|---|---|---|---|---|---|---|---|
| | | | Ave | COV (%) | Ave | COV (%) | Spec. |
| 40-PCL-S | 51.34 | 15.18 | 22.81 | 4.80 | 17.58 | 5.24 | 14.70 |
| 40-MC-N | | | 9.01 | 10.47 | 13.66 | 8.40 | 11.42 |
| 40-MC-S | | 25.22 | 17.43 | 10.52 | 19.17 | 10.43 | 15.89 |
| 40-PCL-N | | | 10.98 | 14.01 | 19.15 | 8.07 | 16.01 |
| 30-PCL-S | 39.41 | 17.27 | 22.81 | 4.80 | 16.02 | 14.20 | 12.29 |
| 30-MC-N | | | 9.01 | 10.47 | 14.85 | 2.23 | 12.42 |
| 30-MC-S | | 27.73 | 17.43 | 10.52 | 13.05 | 5.72 | 10.91 |
| 30-PCL-N | | | 10.98 | 14.01 | 16.52 | 10.66 | 13.63 |
| 20-PCL-S | 25.76 | 16.31 | 22.81 | 4.80 | 16.98 | 5.43 | 14.19 |
| 20-MC-N | | | 9.01 | 10.47 | 14.76 | 9.02 | 12.34 |
| 20-MC-S | | 32.77 | 17.43 | 10.52 | 12.74 | 3.76 | 10.65 |
| 20-PCL-N | | | 10.98 | 14.01 | 13.88 | 8.08 | 11.60 |
| 15-PCL-S | 22.34 | 37.18 | 15.05 | 7.92 | 13.96 | 13.79 | 10.80 |
| 15-MC-N | | | 3.85 | 2.76 | 15.93 | 5.62 | 13.32 |
| 15-MC-S | | | 13.63 | 10.67 | 17.40 | 3.46 | 14.54 |
| 15-PCL-N | | | 7.06 | 13.70 | 12.92 | 8.99 | 10.80 |
| 10-PCL-S | 6.37 | 32.41 | 15.05 | 7.92 | 5.52 | 10.48 | 4.57 |
| 10-MC-N | | | 3.85 | 2.76 | 7.98 | 8.10 | 6.67 |
| 10-MC-S | | | 13.63 | 10.67 | 7.31 | 7.36 | 6.11 |
| 10-PCL-N | | | 7.06 | 13.70 | 7.45 | 16.26 | 5.46 |

Due to the differences in grout strength used in different construction phases for the nominal 20, 30, and 40 MPa units, a direct comparison between the PCL and MC mortar types is difficult to perform for all unit strength values. However, the prisms constructed of 10 and 15 MPa units allow for such a comparison as the grout and masons used during construction were held constant.

An examination of the results for these prisms from Table 4-11 suggests that using type MC mortar results in grouted masonry prisms that are between 20% and 35% stronger than those constructed with type PCL mortar, despite the fact that the compressive strength of the MC mortar was 10% to 45% lower than that for PCL mortar. Further investigation of the effects of mortar type and strength on prism strength for the low-strength units suggest that the effect of MC versus PCL mortar is more significant than the effect of the mortar type, as prisms constructed with type S mortar were between 9% stronger and 14% weaker than prisms constructed with type N mortar, when compared across similar categories. MC mortars contain an air-entraining admixture in order to improve workability, and this has been noted to have an effect on the mortar bond strength and deformation (Hamid and Drysdale, 2005; Melander et al., 1993).

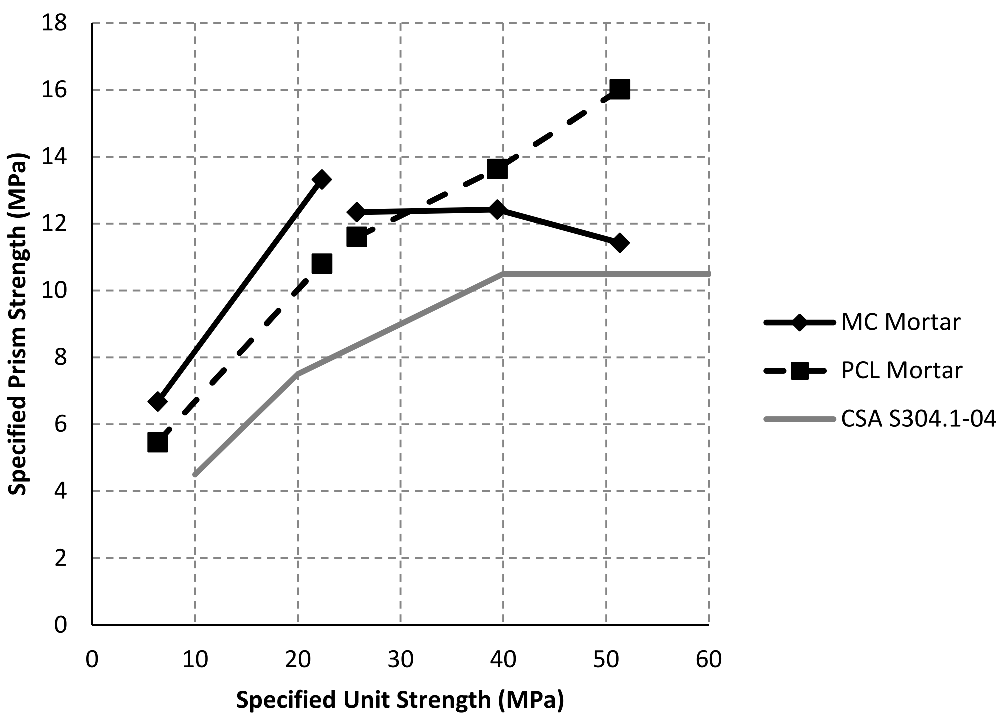



**Figure 4-18: Compressive Strength Test Results for Prisms with Type N Mortar**

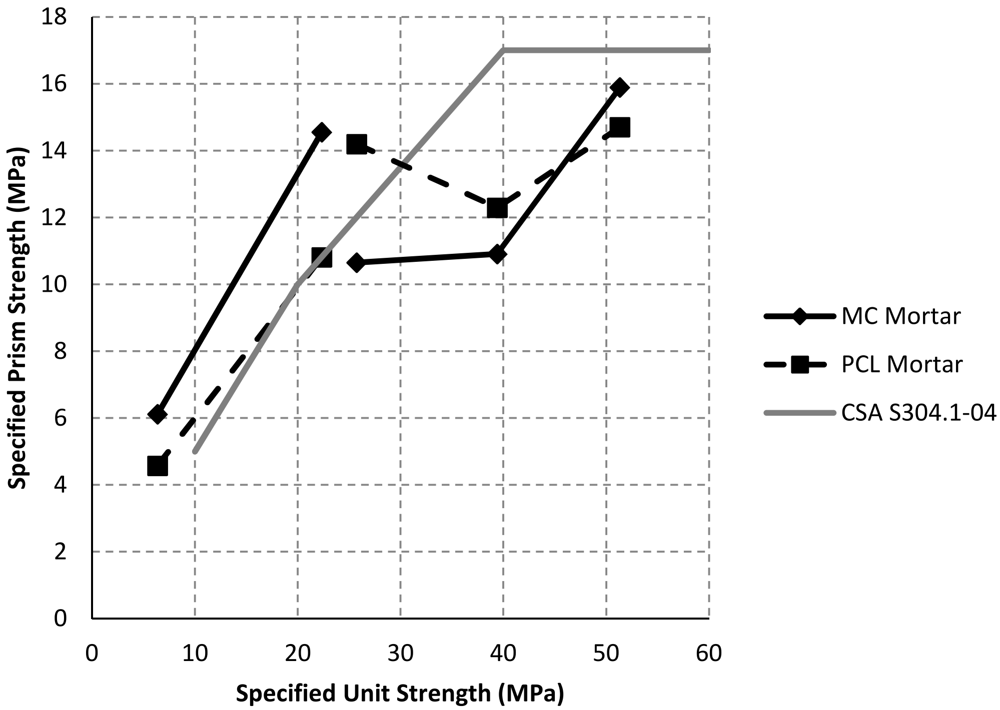



**Figure 4-19: Compressive Strength Test Results for Prisms with Type S Mortar**

Part of the counterintuitive effect of the impact of mortar strength may be due to the similarity between mortar strength and masonry unit strength for the prisms constructed with nominal 10 MPa units. The strength of the mortar joint has not typically been found to have a significant effect on prism strength (Cheema and Klingner, 1986), however in the case of the nominal 10 MPa units the mortar strength varies from 60% to 236% of the unit compressive strength, which is well beyond the range typically considered for design.

As mentioned in the literature review, the misalignment of masonry unit cores has been suggested to lead to stress concentrations in the grout which may decrease the strength of the grouted concrete masonry prism, especially when constructed in a running bond pattern (Khalifa and Magzoub, 1994). An example of this effect is shown in Figure 4-20, which demonstrates a core that was removed following prism testing. The middle course of the grout core has a significantly smaller cross-section than the top or bottom course.

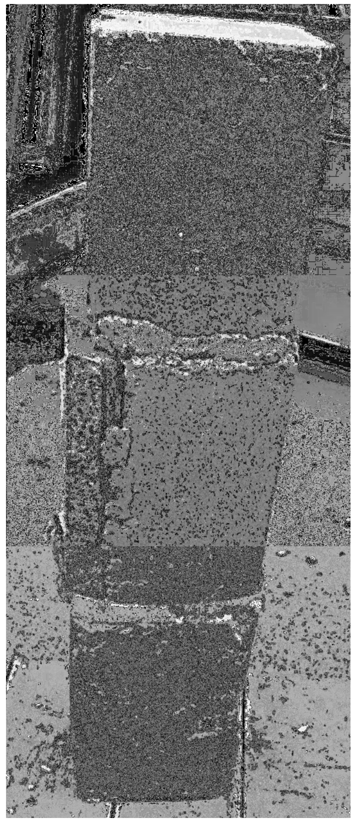


**Figure 4-20: Grout Core Removed from a Tested Prism**

As shown in Figure 4-18, the results for prisms constructed with type N mortar demonstrate a smooth relationship between the specified prism and masonry unit strength for PCL mortar, where the prism strength increases monotonically with unit strength, but the results for MC mortar demonstrate no increase in prism strength for higher strength units.

In Figure 4-19, the results for the prisms constructed with type S mortar demonstrated even less consistent of a trend between prism and unit strength beyond a nominal unit strength of 15 MPa. The prisms constructed in phase 2, with the lowest grout strength and type PCL mortar, on average had a higher compressive strength than the prisms constructed in phase 1.

A noticeable discontinuity in both Figure 4-18 and Figure 4-19 was present between the nominal 15 MPa and 20 MPa unit strength values, due to the change in construction phase. The differences in construction phase included small changes in mortar strength and large changes in grout strength, and these are expected to account for the relatively large prism strength differences between relatively small unit strength differences.

The prisms constructed in phase 2 (low grout strength and MC-N and PCL-S mortars) demonstrated either no strength increase or a slight decrease in strength between the nominal 20 MPa and 40 MPa units. Due to the low grout strength, the ratio of average unit strength to average grout strength for these prisms ranged from 2.02-4.05. Other investigations with similarly high ratios of unit to grout strength have also resulted in relatively weak grouted prism strength, with the effect worsening as the ratio increases (Lee et al., 1994; Hamid et al., 1985; Roman and Romagna, 2002).

The stress-strain curves for prisms constructed with nominal unit strengths of 20 MPa and higher suggest that failure took place within the elastic response range of the masonry prism. This is contrasted with stress-strain curves from the prisms with weaker nominal unit strengths, which demonstrate less of a sudden failure, and smoother post-peak response. The collapse during the elastic response of the prism suggests the failure of the prism is due to premature tensile failure of the masonry units, as found by previous researchers (Hamid et al., 1978; Drysdale and Hamid, 1979).

A summary of test results is presented in Table 4-12 based on interpolation between the points, averaged between the results for MC and PCL mortar. Tests on prisms constructed with type N mortar yielded results that were consistently stronger than the tabulated values in CSA S304.1-04, whereas the prisms constructed with type S mortar yielded results higher than the current standard for lower strength masonry units (less than a specified strength of 20 MPa), but lower than the current standard for higher strength masonry units. These findings are identical in principle, though not to the same magnitude, as the results of the analysis of the database discussed in Chapter 2.

**Table 4-12: Comparison of Prism Test Results to the Current Canadian Standard**

| Specified Unit Strength (MPa) | Type S Mortar | | | Type N Mortar | | |
|---|---|---|---|---|---|---|
| | Specified Prism Strength (MPa) | Computed / Prescribed | Prism* / Unit | Specified Prism Strength (MPa) | Computed / Prescribed | Prism* / Unit |
| 40 | 14.15 | 0.83 | 0.35 | 14.35 | 1.62 | 0.36 |
| 30 | 13.15 | 0.97 | 0.44 | 12.89 | 1.50 | 0.43 |
| 20 | 10.90 | 1.09 | 0.54 | 10.65 | 1.42 | 0.53 |
| 15 | 8.86 | 1.18 | 0.59 | 8.97 | 1.43 | 0.60 |
| 10 | 6.82 | 1.36 | 0.68 | 7.29 | 1.37 | 0.73 |

*Specified prism compressive strength/ specified unit compressive strength

For all prism groups, there was very little difference (only 1-6%) between the strength of grouted prisms constructed with type S and type N mortar, whereas the current Canadian standard specifies that prisms constructed with type S mortar are consistently between 10-50% stronger than those constructed with type N.

As mentioned in the literature review, researchers from the National Concrete Masonry Association (NCMA) in the United States performed a companion investigation with the objective of updating prescribed *f'm* values for the unit strength design method. The results from the NCMA tests, as well as the results from the current testing are presented in Figure 4-21 and Figure 4-22, for type N and type S mortar, respectively.

The results from the NCMA tests show a great degree of similarity with the results presented in this chapter, and interpolate the expected prism strength results accurately between unit strengths of 5 – 20 MPa. As well, up to unit strengths of 35 MPa both sets of results approximate the best-fit line of the full database results very accurately.

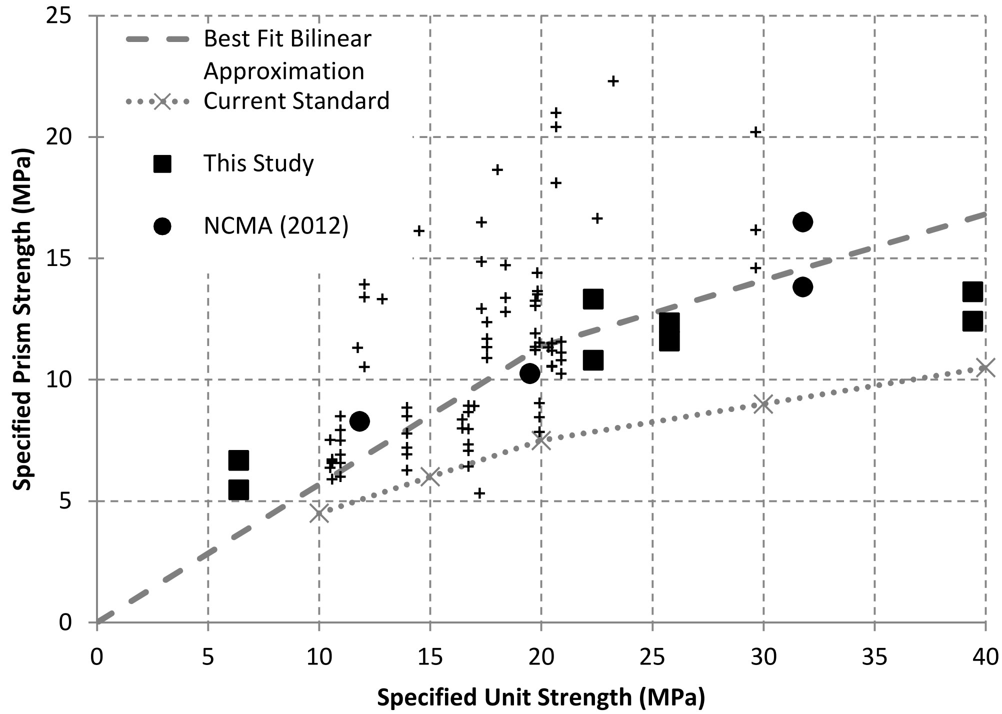



**Figure 4-21: Comparison of Test Results to Previous Investigations for Type N Mortar**

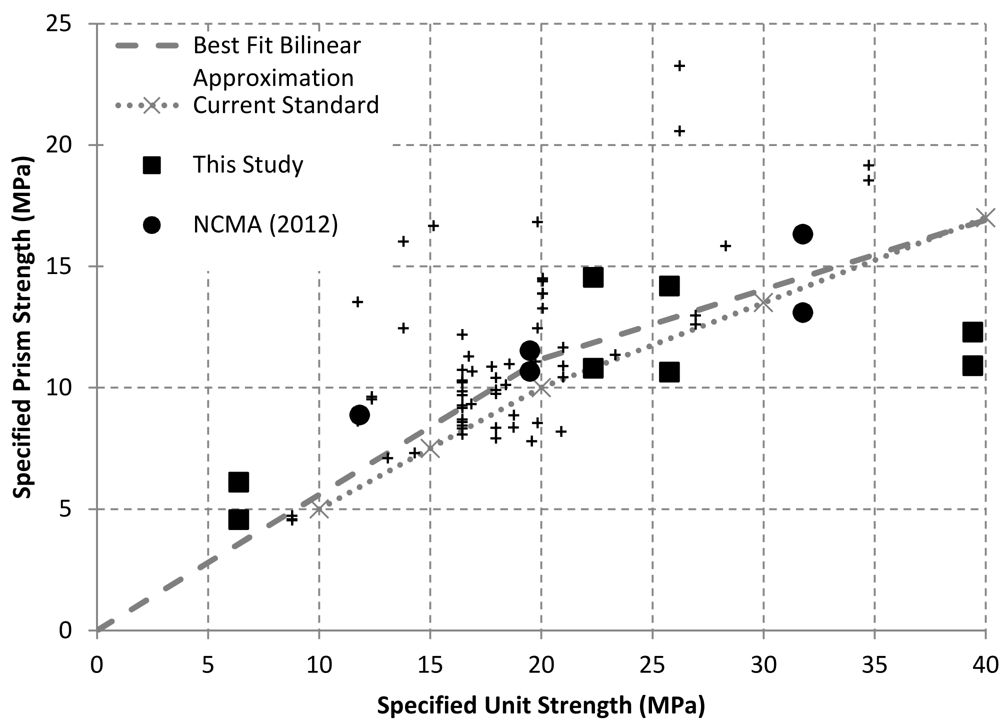



**Figure 4-22: Comparison of Test Results to Previous Investigations for Type S Mortar**

Based on the database of previous test results, as well as the current testing program, a series of proposed *f'm* values are presented in Table 4-13.

**Table 4-13: Proposed Prescribed Values for the Compressive Strength of Grouted Masonry**

| Specified Unit Strength (MPa) | Specified Masonry Compressive Strength (MPa) | | | | | |
|---|---|---|---|---|---|---|
| | Type S Mortar | | | Type N Mortar | | |
| | Current | Proposed | % Change | Current | Proposed | % Change |
| 40 | 17.0 | 15.0 | -12 | 10.5 | 14.0 | 33 |
| 30 | 13.5 | 13.5 | - | 9.0 | 12.5 | 42 |
| 20 | 10.0 | 11.0 | 10 | 7.5 | 10.5 | 40 |
| 15 | 7.5 | 9.0 | 20 | 6.0 | 8.5 | 39 |
| 10 | 5 | 6.5 | 30 | 4.5 | 6.0 | 33 |

# CHAPTER FIVE
# CONCLUSIONS AND RECOMMENDATIONS

While prescribed strength values should be less than measured values, the current values in Table 4 of the Canadian masonry design standard CSA S304.1-04 appear to be overly conservative, particularly for lower strength concrete masonry units which are typically used in masonry construction today. As the value of masonry compressive strength is integral to the design of masonry, this undue conservatism may place concrete masonry systems at a competitive disadvantage.

The following conclusions can be drawn from the test results reported in this thesis:

- There is indeed a high degree of conservatism in the specified masonry compressive strength values prescribed in Table 4 of the current Canadian standard CSA S304.1-04, particularly for prisms constructed with type N mortar. These findings are supported by an examination of prism test results conducted by other researchers.
- Measured specified masonry compressive strength values were found to be 37% – 62% higher than the prescribed values for type N mortar prisms, and 9% – 36% higher than the prescribed values for type S mortar prisms constructed with lower strength units, but 3% – 17% lower for prisms with higher strength units.
- An investigation of available compression test results found strength values 26-60% higher than the prescribed values for type N mortar prisms, 4-12% higher than the prescribed values for type S mortar prisms with lower strength units, but 1% lower than prescribed values for prisms with higher strength units.
- The strength of mortar used in grouted masonry appears to have a minimal effect on prism strength, with less than a 10% strength difference between the prisms constructed with type S and type N mortars. However, current

prescribed masonry compressive strength values in the Canadian masonry design standard CSA S304.1-04 show on average a 30% increase in strength for grouted masonry constructed using type S mortar over the strength of masonry constructed with type N mortar.

- Prisms with masonry units that are significantly stronger than the grout tend to show no increase or even a slight decrease in compressive strength with an increase in unit strength.
- Test results on in-situ grout strength corroborate those reported in past research. The compressive strength ratio of grout cores saw-cut from grouted masonry prisms to grout specimens cast in non-absorbent moulds is in the order of 1.5. Water absorption by the concrete masonry units increases the compressive strength of the in-situ grout when compared to the strength otherwise obtained for the same grout in non-absorbent moulds.

The following recommendations are also made:

- Based on the results of the prism tests performed for this research, the results from the companion study by the National Concrete Masonry Association in the United States, and the analysis of prism strength results from previous investigations, it is proposed that the values in Table 4 of CSA S304.1-04 should be updated to the values in Table 4-13.
- Updates to Table 4 of S304.1-04 should be subject to a reliability analysis to ensure that proper safety factors are maintained in the design standard following limit states design practices.
- Deformational incompatibility between the grout and the masonry units has been previously shown to have a significant impact on prism compressive strength, and is largely due to differences in grout strength. Further research is recommended to better define the range of grout compressive strength values allowed in CSA S304.1-04.

- Although the measured compressive strength of Masonry Cement (MC) mortar used in this investigation was in general lower than the compressive strength of Portland Cement Lime (PCL) mortar, grouted prisms constructed using MC mortar tended to consistently fail at slightly higher loads than similar prisms constructed using PCL mortar. It is recommended that this observed difference be further investigated.

# REFERENCES


1. Ameny, P., Loov, R.E., and Shrive, N.G. (1983) Prediction of Elastic Behaviour of Masonry. International Journal of Masonry Construction, Vol. 3, No. l, pp. 1-9.
2. ASTM C39-12a (2012a) Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA, United States, 7 p.
3. ASTM C140-12a (2012b). Standard Methods of Sampling and Testing Concrete Masonry Units. ASTM International, West Conshohocken, Pennsylvania, USA, 19 p.
4. ASTM C1019 (2012c) Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International, West Conshohocken, PA, United States, 10 p.
5. ASTM C1552-09 (2009) Standard Practice for Capping Concrete Masonry Units, Related Units, and Masonry Prisms for Compression Testing. ASTM International, West Conshohocken, PA, USA, 4 p.
6. Bexton, K.A., Tedos, M.K., and Horton, R.T., (1989) "Compression Strength of Masonry", 5th Canadian Masonry Symposium, Vancouver, British Columbia, pp. 629-639.
7. Boult, B.F. (1979) Concrete Masonry Prism Testing. ACI Journal Technical Paper, Title no. 76-24, vol. 76, no. 4 pp. 513-535.
8. Brown, R. and Melander, J.M. (1999) Flexural Bond Strength of Unreinforced Grouted Masonry Using PCL and MC Mortars. Proceedings of the Eighth North American Masonry Conference, University of Texas at Austin, pp. 694-705.
9. Canadian Standards Association (2004a) A179-04 Mortar and Grout for Unit Masonry, Canadian Standards Association, Mississauga, Ontario, 64 p.
10. Canadian Standards Association (2004b) S304.1-04 Design of Masonry Structures, Canadian Standards Association, Mississauga, Ontario, 148 p.

11. Chahine, G.N. (1989) Behaviour Characteristics of Face Shell Mortared Block Masonry under Axial Compression, M. Eng. Thesis, McMaster University, Hamilton, Canada, 423 p.
12. Cheema, T.S. and Klingner, R.E. (1986) Compressive Strength of Concrete Masonry Prisms. ACI Journal Technical Paper, Title no. 83-11, vol. 83, no. 1, pp. 88-97.
13. Colville, J. and Wolde-Tinsae, A.M. (1990) Compressive Strength of Hollow Concrete Masonry. Proceedings of the Fifth North American Masonry Conference, University of Illinois at Urbania-Champaign, USA, pp. 663-672.
14. Copeland, R.E. and Timms, A.G. (1932) Effects of Mortar Strength and Strength of Units on the Strength of Concrete Masonry Walls. ACI Structural Journal, vol. 28, no. 4, pp. 551-562.
15. Council of Standards Australia (2011) AS 3700-2011 Australian Standard: Masonry Structures, Standards Australia, Sydney, Australia, 161 pp.
16. De Vekey, R.C. (1995) A Statistical Analysis of Masonry Compression Test Data. Proceedings of the Seventh Canadian Masonry Symposium, Hamilton, Ontario, pp. 1140-1151.
17. Dhanesekar, M. (2004) Effect of Grout Confinement on the Compressive Strength of Masonry. Institute of Engineers (India) Journal-CV, Vol. 85, pp. 26-30.
18. Drysdale, R.G. and Hamid, A.A. (1979) Behavior of Concrete Block Masonry under Axial Compression. ACI Journal Technical Paper, Title no. 76-32, vol. 76, no. 6, pp. 707-721.
19. Drysdale, R.G. and Hamid, A.A. (1982) Influence of the Characteristics of the Units on the Strength of Block Masonry. Proceedings of the Second North American Masonry Conference, University of Maryland, 13 pp.
20. Duncan, L. (2008) Effect of Block Face Shell Geometry and Grouting on the Compressive Strength of Concrete Block Masonry. MSc Thesis, University of Windsor, 151 pp.

21. Expocrete (2012) Standard Concrete Masonry Units. Web URL: http://www.expocrete.com/commercial/standard.php
22. Fahmy, E., Ghoneim, T. (1995) Behaviour of Concrete Block Masonry Prisms under Axial Compression. Canadian Journal of Civil Engineering. vol. 22, no. 5, pp. 898-915.
23. Farny, J.A., Melander, J.M., and Greenwald, J.H. (2005) Mortar Quality Assurance: A Review of North American Practices. Proceedings of the tenth Canadian Masonry Symposium, Banff, Canada, pp. 19-30.
24. Ganzerli, S., Rosslow, J., Young, T., Krebs, K., and Mujumdar, V. (2003) Compression Strength Testing for Nonstandard Concrete Masonry Units. Ninth North American Masonry Conference, Clemson, USA, pp. 60-70.
25. Gayed, M., Korany, Y., and Sturgeon, G. (2012) Examination of the Prescribed Concrete Block Masonry Compressive Strength in the Canadian Masonry Design Standard, CSA S304.1-04. 15th International Brick and Block Masonry Conference, Florianópolis, Brazil, 10 pp.
26. Guo, P. (1991) Investigation and Modeling of the Mechanical Properties of Masonry. Doctoral thesis, McMaster University, 414 pp.
27. Hamid, A.A. and Abboud, B.E. (1986) Effect of Block Geometry on the Compressive Strength of Concrete Block Masonry. Proceedings of the Fourth Canadian Masonry Symposium, Fredericton, Canada, pp. 290-298.
28. Hamid, A.A., Abboud, B.E., Harris, H.G. (1985) Direct Modeling of Concrete Block Masonry under Axial Compression. Masonry: Research, Application, and Problems, ASTM STP 871, pp. 151-166.
29. Hamid, A.A and Drysdale, R.G. (2005) Masonry Structures: Behaviour and Design. Canadian Masonry Design Centre, Mississauga, Ontario, 769 p.
30. Hamid, A.A., Drysdale, R.G., Heidebrecht, A. (1978) Effect of Grouting on the Strength Characteristics of Concrete Block Masonry. Report for McMaster University, 17 pp.
31. Hamid, A.A. (1978) Behaviour Characteristics of Concrete Masonry. Doctoral Thesis, McMaster University, 470 pp.

32. Hedstrom, R.O. (1961) Load Tests of Patterned Concrete Masonry Walls. ACI Structural Journal, Title No. 57-54, vol. 57, no. 4, pp. 1265-1286.
33. Hedstrom, E.G. and Hogan, M.B. (1990) The Properties of Masonry Grout in Concrete Masonry. Masonry: Components to Assemblages, ASTM STP J 063, pp. 47-62.
34. Hegemier, G.A., Krishnamoorthy, G., Nunn, R.O., and Moorthy, T.V. (1978) Prism Tests for the Compressive Strength of Concrete Masonry. Proceedings of the North American Masonry Conference, Boulder, USA, pp. 18-1 to 18-17.
35. Ip, F. (1999) Compressive Strength and Modulus of Elasticity of Masonry Prisms. M. Sc. Thesis, Carlton University, 147 pp.
36. Khalaf, F. (1996) Factors Influencing Compressive Strength of Concrete Masonry Prisms. Magazine of Concrete Research, vol. 48, no. 175, pp. 95-101.
37. Khalaf, F., Hendry, A., and Fairbairn, D. (1994) Study of the Compressive Strength of Blockwork Masonry. ACI Structural Journal, vol. 91, no. 4, pp. 367-376.
38. Khalifa, M.A. and Magzoub, A.E. (1994) Compressive Strength of Masonry Prisms. Proceedings of the Structures Congress, Structures Congress XII, pp. 1100-1105.
39. Kingsley, G.R. and Atkinson, R.H. (1986) Comparison of the Behavior of Clay and Concrete Masonry in Compression. Proceedings of the Fourth Canadian Masonry Symposium, Edmonton, Alberta, 12 pp.
40. Korany, Y. and Glanville, J. (2005) Comparing Masonry Compressive Strength in Various Codes. Concrete International, vol. 27, no. 1, pp. 35-39.
41. Lee, R., Longworth, J., Warwaruk, J. (1984) Concrete Masonry Prism Response due to Loads Parallel and Perpendicular to Bed Joints. Structural Engineering Report No. 120, University of Alberta, 90 pp.
42. Long, L., Hamid, A.A., and Drysdale, R.G. (2005) Small-Scale Modeling of Concrete Masonry Using 1/2-Scale Units: A Preliminary Study.

Proceedings of the Tenth Canadian Masonry Symposium, Banff, Canada, pp. 484-493.

43. Maurenbrecher, A.H.P. (1978) Use of the Prism Test to Determine Compressive Strength of Masonry. Proceedings of the North American Masonry Conference, Colorado, USA, pp. 91-2 – 91-13.
44. Maurenbrecher, A.H.P. (1980) Effect of Test Procedures on Compressive Strength of Masonry Prisms. Proceedings of the Second Canadian Masonry Symposium, Ottawa, Canada, pp. 119-132.
45. Maurenbrecher, A.H.P. (1985) Axial Compression Tests on Masonry Walls and Prisms. Proceedings of the Third North American Masonry Conference, University of Texas, USA, pp. 19.1-19.14.
46. Maurenbrecher, A. H. P. (1986) Compressive Strength of Hollow Concrete Blockwork. Proceedings of the 4th Canadian Masonry Symposium, Fredericton, Canada, pp. 997–1009.
47. Melander, J.M., Gosh, S.K., Dubovoy, V.S., Hedstrom, E.G., and Klingner, R.E. (1993) Flexural Bond Strength of Masonry Prisms using Masonry Cement Mortars. Masonry: Materials, Design, Construction, and Maintenance, ASTM STP 1180, Philadelphia, PA, pp. 152-164.
48. National Concrete Masonry Association (2008) NCMA Unit Strength Method Research. Technical Report, National Concrete Masonry Association, Herndon, USA, 10 pp.
49. National Concrete Masonry Association (2012) Recalibration of the Unit Strength Method for Verifying Compliance with the Specified Compressive Strength of Concrete Masonry. Project No. 09-103, Publication No. MR37. National Concrete Masonry Association, Herndon, USA, 98 pp.
50. O'Leary, J.S. (1996) Improved Method for Testing Grout Used as Masonry Cell Fill. Masonry: Esthetics, Engineering and Economy, ASTM STP 1246, pp. 73-87.

51. Ocean Technical Report (1975). Masonry Grout Strength: The Effects of Slump and Absorption. Ocean Construction Supplies Limited, Vancouver, British Columbia, 4 pp.
52. Roberts, J.J. (1973) The Effect of Different Test Procedures Upon the Indicated Strength of Concrete Blocks in Compression. Magazine of Concrete Research, vol. 25, no. 83, pp. 87-98.
53. Roman, H., Romagna, R. (2002) Compressive Strength of Grouted and Un-grouted Concrete Block Masonry. Report for the British Masonry Society, London, vol. 9, pp. 399-404.
54. Sturgeon, B., Ross, M., Korany, Y., and Sturgeon, G. (2013) Grout Strength Measured using Non-Absorbent Mould Specimens and Cores Saw-Cut from Masonry Prisms. 12th Canadian Masonry Symposium, Vancouver, Canada, 10 pp.
55. Sturgeon, G.R., Longworth, J., and Warwaruk, J. (1989) An Investigation of Reinforced Concrete Block Masonry Columns. Department of Civil Engineering, University of Alberta, Canada, 378 pp.
56. Thomas, R.D., and Mujumdar, V. (2003) Determining Concrete Masonry Unit Compressive Strength Using Coupon Testing. Masonry: Opportunities in the 21st Century, ASTM STP 1432, ASTM International, PA, pp. 138-152.
57. Thompson, J.J., Walloch, C.T., and Thomas, R.D. (2002) Predicting Grouted Concrete Masonry Prism Strength. Masonry: Opportunities in the 21st Century, ASTM STP 1432, ASTM International, PA, pp. 170-185.
58. Yao, C., and Nathan, N.D. (1989) Axial Capacity of Grouted Concrete Masonry, Proceedings of the Fifth Canadian Masonry Symposium, Vancouver, Canada, pp. 45-54.
59. Yi, S., Yang, E., and Choi, J. (2006) Effect of Specimen Sizes, Specimen Shapes, and Placement Directions on Compressive Strength of Concrete, Nuclear Engineering and Design 236, pp. 115-127.

# APPENDIX A:
# REFERENCES USED TO CONSTRUCT THE DATABASE


1. Ahmadi, B. (2001) Performance of Grouted Masonry Walls under Severe Environment. Proceedings of the Third International Conference on Concrete under Severe Conditions, pp. 65-70.
2. Baba, A., and Senbu, O. (1986) Influencing Factors on Prism Strength of Grouted Masonry and Fracture Mechanism under Uniaxial Loading. Fourth Canadian Masonry Symposium, vol. 2, University of New Brunswick, pp. 1081-1096.
3. Bexton, K.A., Tedos, M.K., and Horton, R.T., (1989) "Compression Strength of Masonry", 5th Canadian Masonry Symposium, Vancouver, British Columbia, pp. 629-639.
4. Boult, B.F. (1979) Concrete Masonry Prism Testing. ACI Journal Technical Paper, Title no. 76-24, vol. 76, no. 4, pp. 513-535.
5. Cheema, T.S. and Klingner, R.E. (1986) Compressive Strength of Concrete Masonry Prisms. ACI Journal Technical Paper, Title no. 83-11, vol. 83, no. 1, pp. 88-97.
6. Dhanasekar, M. (2004) Effect of Grout Confinement on the Compressive Strength of Masonry. Institute of Engineers (India) Journal-CV, vol. 85, pp. 26-30.
7. Dhanasekar, M. and Shrive, N.G. (2002) Strength and Deformation of Confined and Unconfined Grouted Concrete Masonry. ACI Structural Journal, vol. 99, no. 6, pp. 819-826.
8. Drysdale, R.G. and Hamid, A.A. (1979) Behavior of Concrete Block Masonry under Axial Compression. ACI Journal Technical Paper, Title no. 76-32, vol. 76, no. 6, pp. 707-721.
9. Drysdale, R.G. and Hamid, A.A. (1983) Capacity of Concrete Block Masonry Prisms under Eccentric Compressive Loading. ACI Journal Technical Paper, Title no. 80-11, vol. 80, no. 2, pp. 102-108.

10. Duncan, L. (2008) Effect of Block Face Shell Geometry and Grouting on the Compressive Strength of Concrete Block Masonry. MSc Thesis, University of Windsor, 151 pp.
11. Fahmy, E., Ghoneim, T. (1995) Behaviour of Concrete Block Masonry Prisms under Axial Compression. Canadian Journal of Civil Engineering. vol. 22, pp. 898-915.
12. Guo, P. (1991) Investigation and Modeling of the Mechanical Properties of Masonry. Doctoral thesis, McMaster University, 414 pp.
13. Hamid, A.A., Abboud, B.E., Harris, H.G. (1985) Direct Modeling of Concrete Block Masonry under Axial Compression. Masonry: Research, Application, and Problems, ASTM STP 871, pp. 151-166.
14. Hamid, A.A., Drysdale, R.G., Heidebrecht, A. (1978) Effect of Grouting on the Strength Characteristics of Concrete Block Masonry. Report for McMaster University, 17 pp.
15. Hawk, S.W., McLean, D.I., Young, T.C. (1997) Compressive Behavior of Insulated Concrete Masonry Prisms. The Masonry Society Journal, vol. 15, no. 2, pp. 53-60.
16. Hou, J. (2006) Strain Gradient Effect on the Behaviour and Strength of Masonry Prisms. Master's Thesis, Dalhousie University, 128 pp.
17. Khalaf, F. (1996) Factors Influencing Compressive Strength of Concrete Masonry Prisms. Magazine of Concrete Research, vol. 48, no. 175, pp. 95-101.
18. Khalaf, F., Hendry, A., and Fairbairn, D. (1994) Study of the Compressive Strength of Blockwork Masonry. ACI Structural Journal, vol. 91, no. 4, pp. 367-376.
19. Khattab, M. (1993) In-Plane Behaviour of Grouted Concrete Masonry under Biaxial States of Stress. PhD Thesis, McMaster University, 434 pp.
20. Kingsley, G.R. and Atkinson, R.H. (1986) Comparison of the Behavior of Clay and Concrete Masonry in Compression. Proceedings of the Fourth Canadian Masonry Symposium, Edmonton, Alberta, 12 pp.

21. Kingsley, G.R., Atkinson, R.H., Noland, J.L., and Hart, G.C. (1989) The Effect of Height on Stress-Strain Measurements on Grouted Concrete Masonry Prisms. Proceedings of the Fifth Canadian Masonry Symposium, Vancouver, 17 pp.
22. Lee, R., Longworth, J., Warwaruk, J. (1984) Concrete Masonry Prism Response due to Loads Parallel and Perpendicular to Bed Joints. Structural Engineering Report No. 120, University of Alberta, 90 pp.
23. Liu, L., Wang, Z., Zhai, C., Zhai, X. (2009) Experimental Research on Biaxial Compressive Strength of Grouted Concrete Block Masonry. Advances in Structural Engineering, vol. 12, no. 4, pp. 451-461.
24. Long, L., Hamid, A.A., and Drysdale, R.G. (2005) Small-Scale Modeling of Concrete Masonry Using 1/2-Scale Units: A Preliminary Study. Proceedings of the Tenth Canadian Masonry Symposium, Banff, Canada, pp. 484-493.
25. National Concrete Masonry Association (2012) Recalibration of the Unit Strength Method for Verifying Compliance with the Specified Compressive Strength of Concrete Masonry. Project No. 09-103, Publication No. MR37. National Concrete Masonry Association, Herndon, USA, 98 pp.
26. Olatunji, T., Warwaruk, J., Longworth, J. (1986) Behavior and Strength of Masonry Wall/Slab Joints. University of Alberta Department of Civil Engineering Structural Engineering Report 139, 247 pp.
27. Priestley, M.J.N., and Elder, D.M. (1983) Stress-Strain Curves for Unconfined and Confined Concrete Masonry. ACI Journal Technical Paper, Title no. 80-19, vol. 80, no. 3, pp. 192-201.
28. Roman, H., Romagna, R. (2002) Compressive Strength of Grouted and Un-grouted Concrete Block Masonry. Report for the British Masonry Society, London, vol. 9, pp. 399-404.
29. Sakr, K.M., and Neis, V.V. (1989) Some Studies on the Stress-Strain Behaviour of Grouted Concrete Masonry Block Units. Proceedings of the Fifth Canadian Masonry Symposium, Vancouver, Canada, pp. 619-629.

30. Scrivener, J., Baker, L. (1988) Factors Influencing Grouted Masonry Prism Compressive Strength. Proceedings of the Eighth International Brick and Block Masonry Conference, Dublin, Ireland, pp. 875-883.

31. Thompson, J.J., Walloch, C.T., and Thomas, R.D. (2002) Predicting Grouted Concrete Masonry Prism Strength. Masonry: Opportunities in the 21st Century, ASTM STP 1432, ASTM International, PA, pp. 170-185.

32. Wang, R., Elwi, A.E., Hatzinikolas, M.A., Warwaruk, J. (1997) Tests of Tall Cavity Walls Subjected to Eccentric Loading. Journal of Structural Engineering, vol. 123, no. 7, pp. 912-919.

33. Wong, H.E, and Drysdale, R.G. (1985) Compression Characteristics of Concrete Block Masonry Prisms. Masonry: Research, Application, and Problems, ASTM STP 871, pp. 167-177.

34. Xiao, X., and Lu, X. (1997) Study on Bearing Capacity of Concrete Masonry. 11th International Brick/Block Masonry Conference. Tongji University, China, pp. 1290-1297.

35. Yao, C., and Nathan, N.D. (1989) Axial Capacity of Grouted Concrete Masonry, Proceedings of the Fifth Canadian Masonry Symposium, Vancouver, Canada, pp. 45-54.

36. Zhu, Y.J. (2002) Experimental Study of Dynamic Analysis of Mechanical Properties of High Strength Concrete Block Masonry. PhD Thesis, Northeastern University, China, 156 pp.

# APPENDIX B:
# INDIVIDUAL MATERIAL TEST RESULTS

**Table B-1: Test Results for CMU Compressive Testing**

| Nominal Unit Strength (MPa) | Compressive Strength | | | | Modulus of Elasticity | | |
|---|---|---|---|---|---|---|---|
| | Per Unit (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Unit (MPa) | Average (MPa) | COV (%) |
| 10 | 7.67 | 7.61 | 3.45 | 6.37 | 1070.11 | 932.59 | 17.82 |
| | 7.96 | | | | 1046.79 | | |
| | 7.61 | | | | 1014.38 | | |
| | 7.61 | | | | 855.89 | | |
| | 7.22 | | | | 675.79 | | |
| 15 | 26.99 | 26.71 | 3.13 | 22.33 | 3313.24 | 3311.92 | 13.40 |
| | 25.66 | | | | 2560.31 | | |
| | 27.55 | | | | 3713.79 | | |
| | 26.00 | | | | 3474.45 | | |
| | 27.35 | | | | 3497.81 | | |
| 20 | 36.50 | 33.00 | 13.38 | 25.76 | + | 3707.59 | 4.82 |
| | 36.94 | | | | + | | |
| | 32.27 | | | | 3571.08 | | |
| | 33.29 | | | | 3909.67 | | |
| | 25.94 | | | | 3642.00 | | |
| 30 | 46.33 | 47.13 | 2.15 | 39.40 | 5249.62 | 5190.72 | 1.34 |
| | 47.98 | | | | 5229.85 | | |
| | 47.06 | | | | 5125.58 | | |
| | 48.31 | | | | 5104.63 | | |
| | 45.97 | | | | 5243.94 | | |
| 40 | 58.70 | 61.42 | 7.57 | 51.35 | + | 6198.34 | 3.82 |
| | 58.30 | | | | 6017.22 | | |
| | 57.47 | | | | 5971.36 | | |
| | 64.45 | | | | 6389.89 | | |
| | 68.10 | | | | 6414.89 | | |

+: Stress-strain data was not collected during this test.

**Table B-2: Single Variable ANOVA Analysis for CMU Strength**

SUMMARY

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Nominal 15 MPa | 5 | 133.597 | 26.7194 | 0.70022 |
| Nominal 20 MPa | 5 | 164.996 | 32.9992 | 19.4846 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 98.58779 | 1 | 98.58779 | 9.768501 | 0.014112 | 5.317655 |
| Within Groups | 80.73934 | 8 | 10.09242 | | | |
| | | | | | | |
| Total | 179.3271 | 9 | | | | |

**Table B-3: Masonry Unit Water Absorption Results**

| Nominal Unit Strength (MPa) | Weight Dried (kg) | Weight Saturated (kg) | 24 Hour Moisture Absorption (%) | Average | COV (%) |
|---|---|---|---|---|---|
| 10 | 7.10 | 7.82 | 10.14 | 10.17 | 2.21 |
| | 7.03 | 7.73 | 9.96 | | |
| | 6.92 | 7.64 | 10.40 | | |
| 15 | 7.74 | 8.82 | 13.95 | 14.11 | 1.06 |
| | 7.72 | 8.82 | 14.25 | | |
| | 7.78 | 8.88 | 14.14 | | |
| 20 | 8.10 | 8.98 | 10.86 | 10.59 | 2.70 |
| | 8.16 | 9.00 | 10.29 | | |
| | 8.10 | 8.96 | 10.62 | | |
| 30 | 8.78 | 9.52 | 8.43 | 7.95 | 5.82 |
| | 9.10 | 9.82 | 7.91 | | |
| | 9.06 | 9.74 | 7.51 | | |
| 40 | 9.36 | 9.88 | 5.56 | 5.76 | 7.33 |
| | 9.28 | 9.86 | 6.25 | | |
| | 9.48 | 10.00 | 5.49 | | |

**Table B-4: Mortar Cube Test Results**

| Construction Phase | Mortar Type | Compressive Strength (MPa) | Average Strength (MPa) | COV (%) |
|---|---|---|---|---|
| 1 | MC-S | 18.20 | 17.43 | 10.52 |
| | | 18.72 | | |
| | | 15.36 | | |
| | | 16.64 | | |
| | | 20.00 | | |
| | | 15.68 | | |
| | PCL-N | 10.00 | 10.98 | 14.01 |
| | | 10.92 | | |
| | | 12.00 | | |
| | | 12.04 | | |
| | | 8.44 | | |
| | | 12.48 | | |
| 2 | MC-N | 9.00 | 9.01 | 10.47 |
| | | 7.24 | | |
| | | 9.52 | | |
| | | 8.84 | | |
| | | 9.80 | | |
| | | 9.64 | | |
| | PCL-S | 21.92 | 22.81 | 4.80 |
| | | 22.76 | | |
| | | 24.24 | | |
| | | 21.64 | | |
| | | 22.28 | | |
| | | 24.04 | | |
| 3 | MC-N | 3.72 | 3.85 | 2.76 |
| | | 3.92 | | |
| | | 3.96 | | |
| | | 3.88 | | |
| | | 3.92 | | |
| | | 3.72 | | |
| | MC-S | 12.88 | 13.63 | 10.67 |
| | | 14.68 | | |
| | | 15.16 | | |
| | | 12.76 | | |
| | | 14.80 | | |
| | | 11.52 | | |
| | PCL-N | 8.44 | 7.06 | 13.70 |
| | | 7.28 | | |
| | | 6.36 | | |
| | | 7.12 | | |
| | | 7.52 | | |
| | | 5.64 | | |
| | PCL-S | 16.28 | 15.05 | 7.92 |
| | | 14.08 | | |
| | | 14.52 | | |
| | | 15.84 | | |
| | | 16.12 | | |
| | | 13.44 | | |

**Table B-5: Grout Strength from Non-Absorbent Mould Samples**

| Construction Phase | Compressive Strength (MPa) | Average Strength (MPa) | COV (%) |
|---|---|---|---|
| 1a* | 24.36 | 27.99 | 7.32 |
| | 28.00 | | |
| | 30.15 | | |
| | 28.57 | | |
| | 25.74 | | |
| | 30.28 | | |
| | 29.54 | | |
| | 26.52 | | |
| | 28.78 | | |
| 1b* | 33.97 | 28.47 | 11.48 |
| | 29.18 | | |
| | 30.23 | | |
| | 27.31 | | |
| | 28.27 | | |
| | 31.84 | | |
| | 25.64 | | |
| | 23.25 | | |
| | 26.56 | | |
| 2 | 10.10 | 10.60 | 4.54 |
| | 10.56 | | |
| | 10.11 | | |
| | 10.61 | | |
| | 11.36 | | |
| | 10.90 | | |
| 3 | 23.52 | 22.16 | 6.56 |
| | 23.47 | | |
| | 20.09 | | |
| | 22.84 | | |
| | 20.66 | | |
| | 22.37 | | |

*: Construction of the prisms for Phase 1 took place over two consecutive days, and as such grout samples were taken from both days.

**Table B-6: Single Variable ANOVA Analysis for Phase 1 Grout Samples**

SUMMARY

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| Day1 | 9 | 251.9385 | 27.99316 | 4.203598 |
| Day2 | 9 | 256.2471 | 28.4719 | 10.68916 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 1.031356 | 1 | 1.031356 | 0.138504 | 0.714656 | 4.493998 |
| Within Groups | 119.1421 | 16 | 7.446379 | | | |
| | | | | | | |
| Total | 120.1734 | 17 | | | | |

**Table B-7: Prismatic Grout Samples Removed from Untested Prisms**

| **Nominal Unit Strength (MPa)** | **Construction Phase** | **Compressive Strength (MPa)** | **Average Strength (MPa)** | **COV (%)** |
|---|---|---|---|---|
| 20 | 1 | 35.41 | 32.77 | 8.08 |
| | | 35.52 | | |
| | | 30.23 | | |
| | | 32.55 | | |
| | | 30.13 | | |
| 30 | | 33.75 | 29.50 | 14.39 |
| | | 33.05 | | |
| | | 30.67 | | |
| | | 24.79 | | |
| | | 25.26 | | |
| 40 | | 26.07 | 25.22 | 3.38 |
| | | 24.25 | | |
| | | 25.83 | | |
| | | 25.58 | | |
| | | 24.67 | | |
| 20 | 2 | 18.49 | 16.31 | 13.36 |
| | | 16.51 | | |
| | | 14.04 | | |
| | | 18.39 | | |
| | | 14.13 | | |
| 30 | | 18.53 | 17.27 | 7.30 |
| | | 18.00 | | |
| | | 18.01 | | |
| | | 15.81 | | |
| | | 16.02 | | |

| | | | | |
|---|---|---|---|---|
| 40 | | 16.15 | 15.18 | 6.36 |
| | | 16.10 | | |
| | | 14.17 | | |
| | | 15.27 | | |
| | | 14.22 | | |
| 10 | 3 | 33.91 | 32.41 | 4.50 |
| | | 34.04 | | |
| | | 32.00 | | |
| | | 31.21 | | |
| | | 30.92 | | |
| 15 | | 39.13 | 37.18 | 5.27 |
| | | 38.51 | | |
| | | 38.12 | | |
| | | 34.92 | | |
| | | 35.24 | | |

# APPENDIX C:
# INDIVIDUAL PRISM TEST RESULTS

**Table C-1: Individual Prism Results for Prisms with 10 MPa Units**

| Prism Designation | Compressive Strength | | | | | Young's Modulus | | |
|---|---|---|---|---|---|---|---|---|
| | Per Prism (MPa) | Adjusted* (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Prism (GPa) | Average Modulus (GPa) | COV (%) |
| 10-MC-N | 8.83 | 7.94 | 7.98 | 8.10 | 6.67 | 18.91 | 18.52 | 14.35 |
| | 9.95 | 8.96 | | | | 19.87 | | |
| | 7.93 | 7.14 | | | | 17.48 | | |
| | 8.79 | 7.91 | | | | 21.69 | | |
| | 8.85 | 7.97 | | | | 14.63 | | |
| 10-MC-S | 8.67 | 7.80 | 7.31 | 7.36 | 6.11 | 19.12 | 17.33 | 18.82 |
| | 8.69 | 7.82 | | | | 19.08 | | |
| | 7.42 | 6.68 | | | | 13.55 | | |
| | 7.57 | 6.81 | | | | 14.14 | | |
| | 8.27 | 7.45 | | | | 20.77 | | |
| 10-PCL-N | 6.49 | 5.84 | 7.45 | 16.26 | 5.46 | 9.25 | 17.12 | 27.35 |
| | 6.39 | 5.75 | | | | 12.21 | | |
| | 9.90 | 8.91 | | | | 17.90 | | |
| | 8.57 | 7.72 | | | | 18.03 | | |
| | 8.41 | 7.57 | | | | 21.92 | | |
| | 9.22 | 8.30 | | | | 19.42 | | |
| | 8.95 | 8.06 | | | | 21.09 | | |
| 10-PCL-S | 6.49 | 5.85 | 5.52 | 10.48 | 4.57 | 14.82 | 12.92 | 26.47 |
| | 6.84 | 6.15 | | | | 13.68 | | |
| | 6.31 | 5.68 | | | | 8.74 | | |
| | 5.17 | 4.65 | | | | 10.21 | | |
| | 5.88 | 5.29 | | | | 17.13 | | |

*Adjusted: Maximum stress factored by 0.9 to account for height-to-thickness effects.
Two additional prisms in the 10-PCL-N series were tested as the coefficient of variation was greater than 15%.

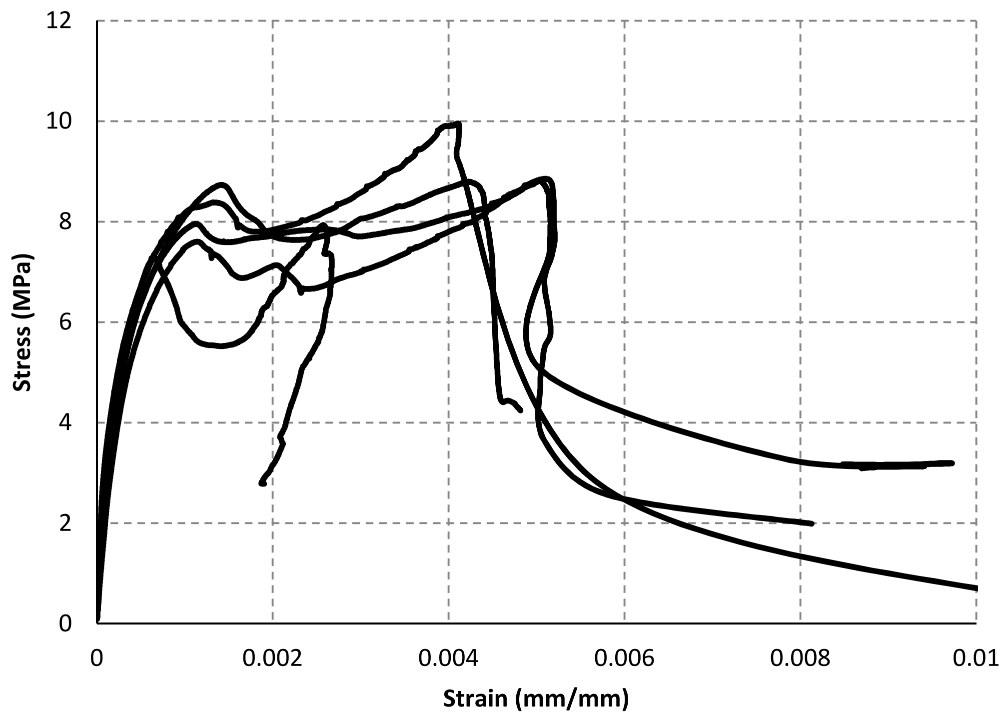



**Figure C-1: Stress-Strain Curves for 10-MC-N Prisms**

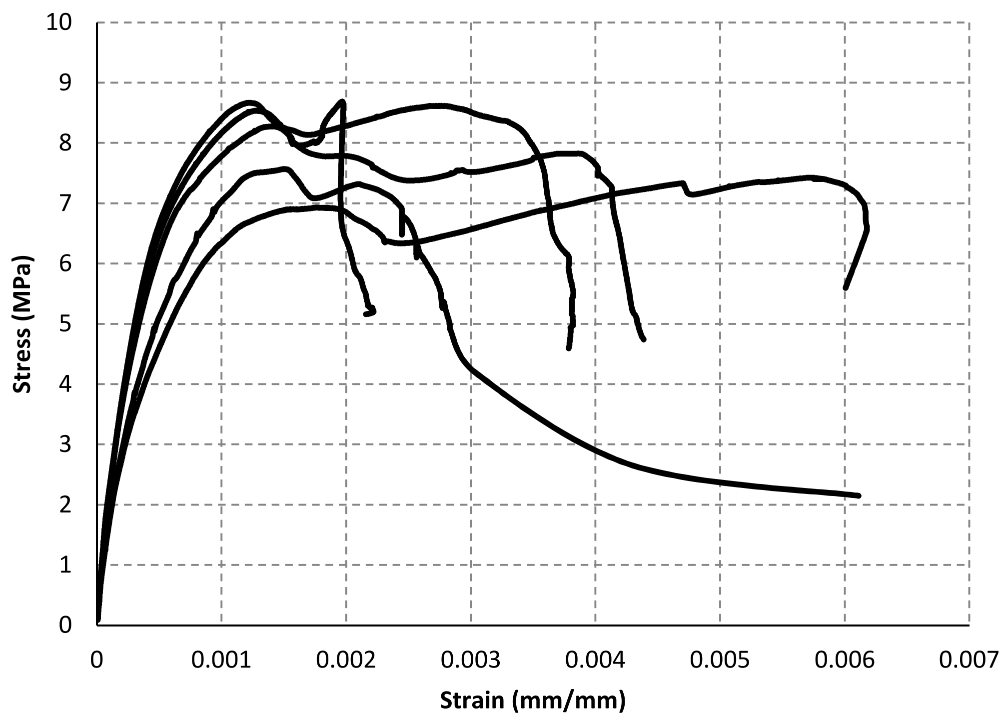



**Figure C-2: Stress-Strain Curves for 10-MC-S Prisms**

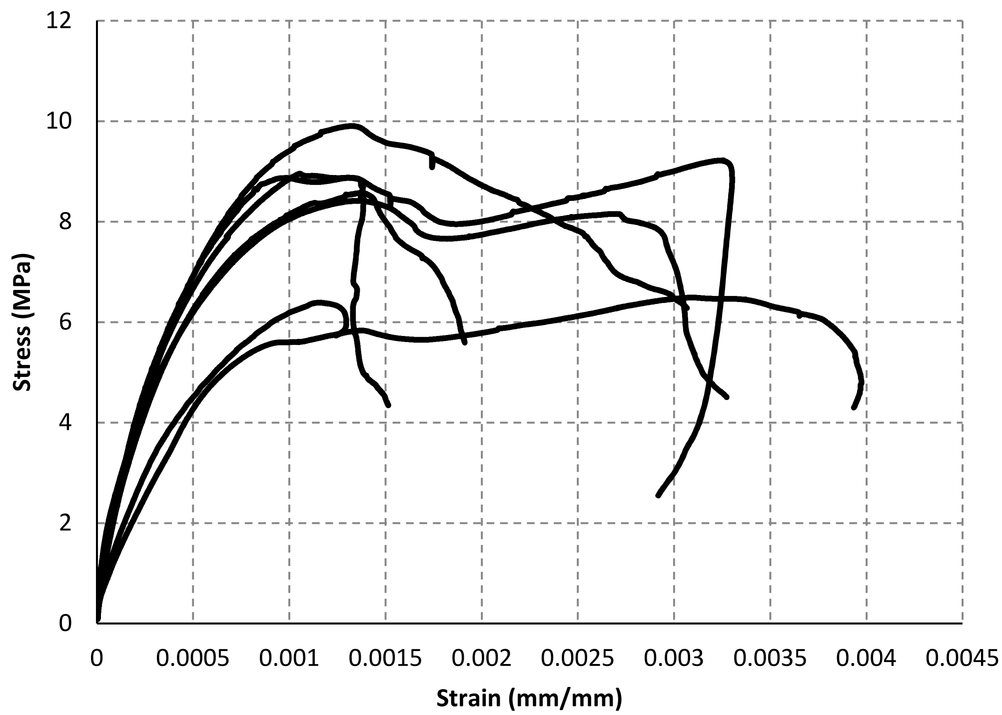



**Figure C-3: Stress-Strain Curves for 10-PCL-N Prisms**

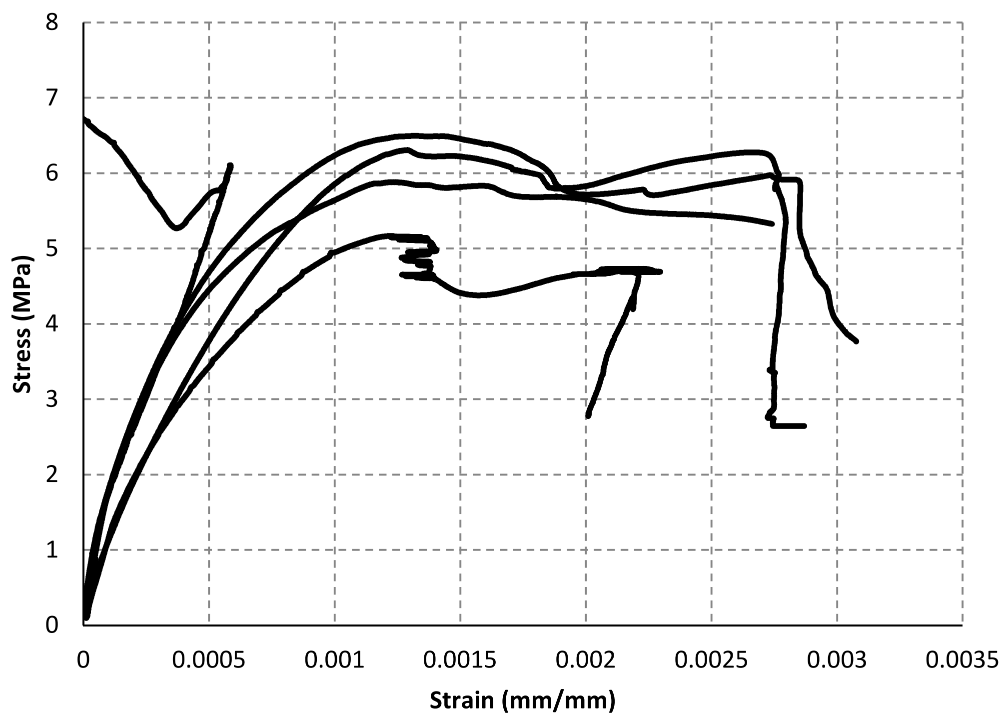



**Figure C-4: Stress-Strain Curves for 10-PCL-S Prisms**

**Table C-2: Individual Prism Results for Prisms with 15 MPa Units**

| Prism Designation | Compressive Strength | | | | | Young's Modulus | | |
|---|---|---|---|---|---|---|---|---|
| | Per Prism (MPa) | Adjusted* (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Prism (GPa) | Average Modulus (GPa) | COV (%) |
| 15-MC-N | 18.09 | 16.28 | 15.93 | 5.62 | 13.32 | 21.56 | 23.75 | 11.42 |
| | 18.44 | 16.60 | | | | 27.56 | | |
| | 15.95 | 14.35 | | | | 25.60 | | |
| | 18.00 | 16.20 | | | | 22.54 | | |
| | 18.02 | 16.22 | | | | 21.48 | | |
| 15-MC-S | 19.21 | 17.29 | 17.40 | 3.46 | 14.54 | 23.70 | 24.65 | 4.30 |
| | 19.73 | 17.76 | | | | 23.87 | | |
| | 19.76 | 17.79 | | | | 25.85 | | |
| | 18.21 | 16.39 | | | | 24.08 | | |
| | 19.74 | 17.76 | | | | 25.76 | | |
| 15-PCL-N | 15.20 | 13.68 | 12.92 | 8.99 | 10.80 | 23.81 | 20.72 | 9.11 |
| | 15.51 | 13.96 | | | | 19.50 | | |
| | 15.15 | 13.64 | | | | 21.27 | | |
| | 12.82 | 11.54 | | | | 19.57 | | |
| | 13.08 | 11.77 | | | | 19.47 | | |
| 15-PCL-S | 17.54 | 15.79 | 13.96 | 13.79 | 10.80 | 27.94 | 23.69 | 13.74 |
| | 18.09 | 16.28 | | | | 26.28 | | |
| | 13.92 | 12.52 | | | | 22.44 | | |
| | 13.52 | 12.17 | | | | 20.46 | | |
| | 14.50 | 13.05 | | | | 21.32 | | |

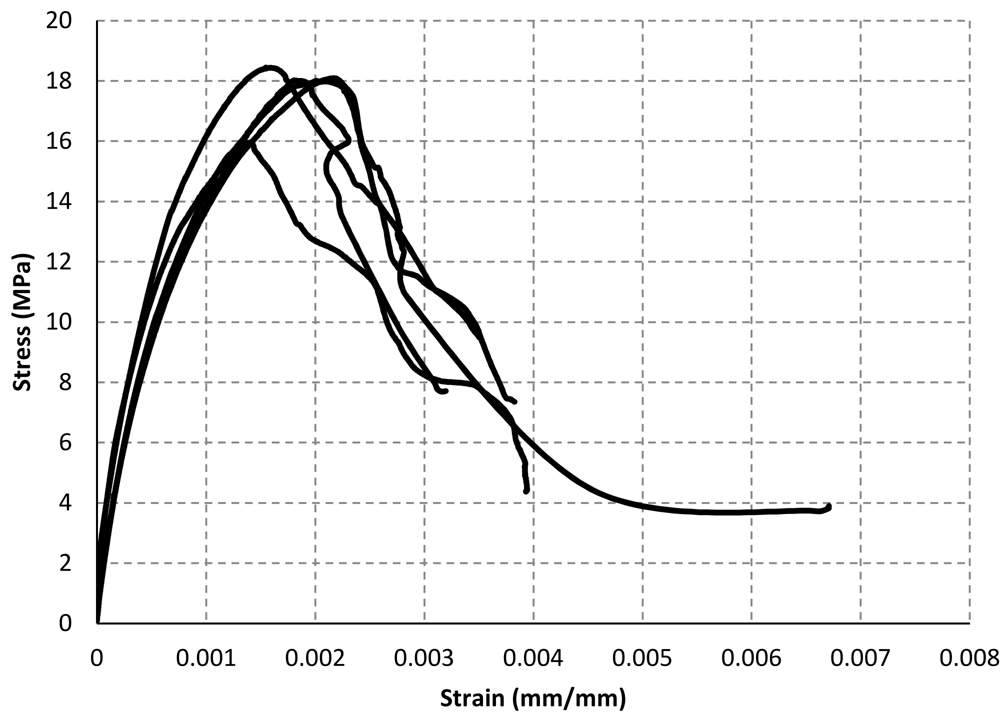



**Figure C-5: Stress-Strain Curves for 15-MC-N Prisms**

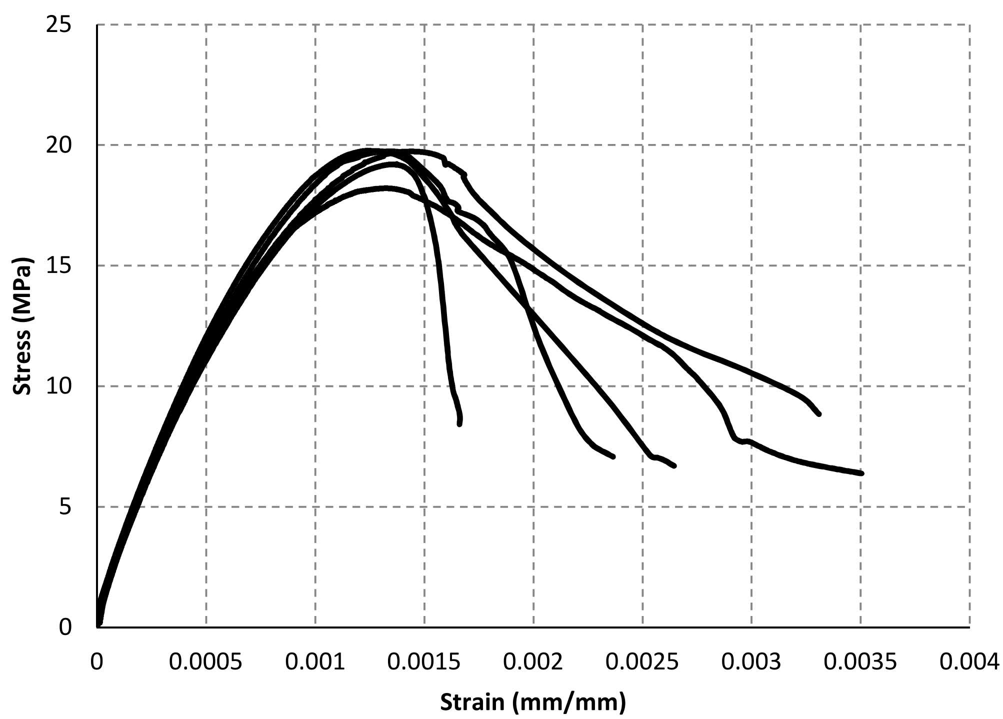



**Figure C-6: Stress-Strain Curves for 15-MC-S Prisms**

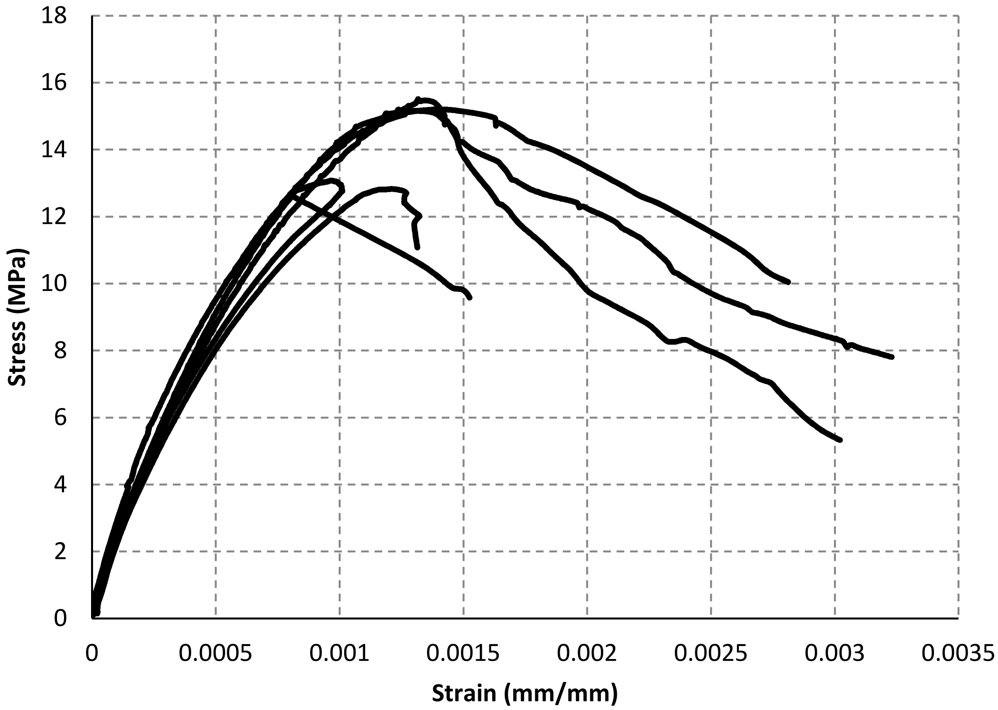



**Figure C-7: Stress-Strain Curves for 15-PCL-N Prisms**

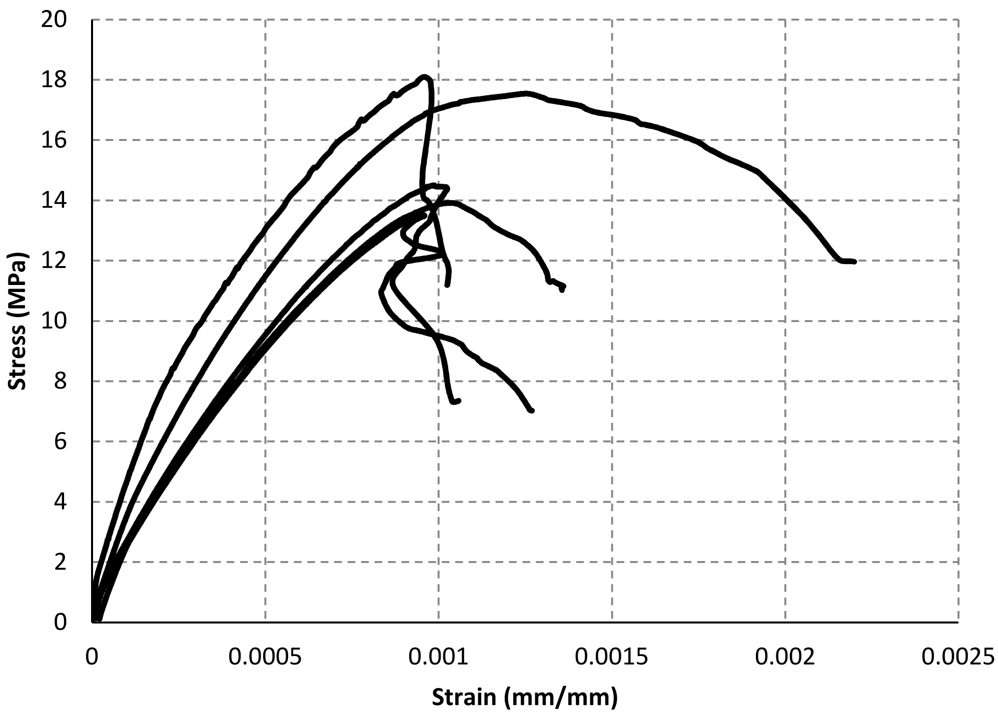



**Figure C-8: Stress-Strain Curves for 15-PCL-S Prisms**

**Table C-3: Individual Prism Results for Prisms with 20 MPa Units**

| Prism Designation | Compressive Strength | | | | | Young's Modulus | | |
|---|---|---|---|---|---|---|---|---|
| | Per Prism (MPa) | Adjusted* (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Prism (GPa) | Average Modulus (GPa) | COV (%) |
| 20-MC-N | 15.83 | 14.24 | 14.76 | 9.02 | 12.34 | 15.06 | 17.00 | 8.54 |
| | 15.10 | 13.59 | | | | 16.31 | | |
| | 16.72 | 15.05 | | | | 18.44 | | |
| | 18.83 | 16.94 | | | | 18.43 | | |
| | 15.54 | 13.98 | | | | 16.74 | | |
| 20-MC-S | 14.26 | 12.84 | 12.74 | 3.76 | 10.65 | 17.61 | 21.63 | 19.07 |
| | 13.74 | 12.37 | | | | 20.75 | | |
| | 13.65 | 12.29 | | | | 21.66 | | |
| | 14.10 | 12.69 | | | | 19.65 | | |
| | 14.99 | 13.49 | | | | 28.50 | | |
| 20-PCL-N | 13.67 | 12.30 | 13.88 | 8.08 | 11.60 | + | 17.36 | 4.42 |
| | 16.47 | 14.82 | | | | 17.71 | | |
| | 16.18 | 14.56 | | | | 18.04 | | |
| | 16.24 | 14.62 | | | | 16.27 | | |
| | 14.53 | 13.07 | | | | 17.41 | | |
| 20-PCL-S | 18.07 | 16.27 | 16.98 | 5.43 | 14.19 | 26.15 | 25.19 | 2.64 |
| | 17.61 | 15.85 | | | | 24.48 | | |
| | 19.62 | 17.66 | | | | 24.66 | | |
| | 20.06 | 18.05 | | | | 25.37 | | |
| | 18.95 | 17.05 | | | | 25.28 | | |

*Adjusted: Maximum stress factored by 0.9 to account for height-to-thickness effects.

+: An error in the data logging system resulted in faulty stress-strain readings for this test.

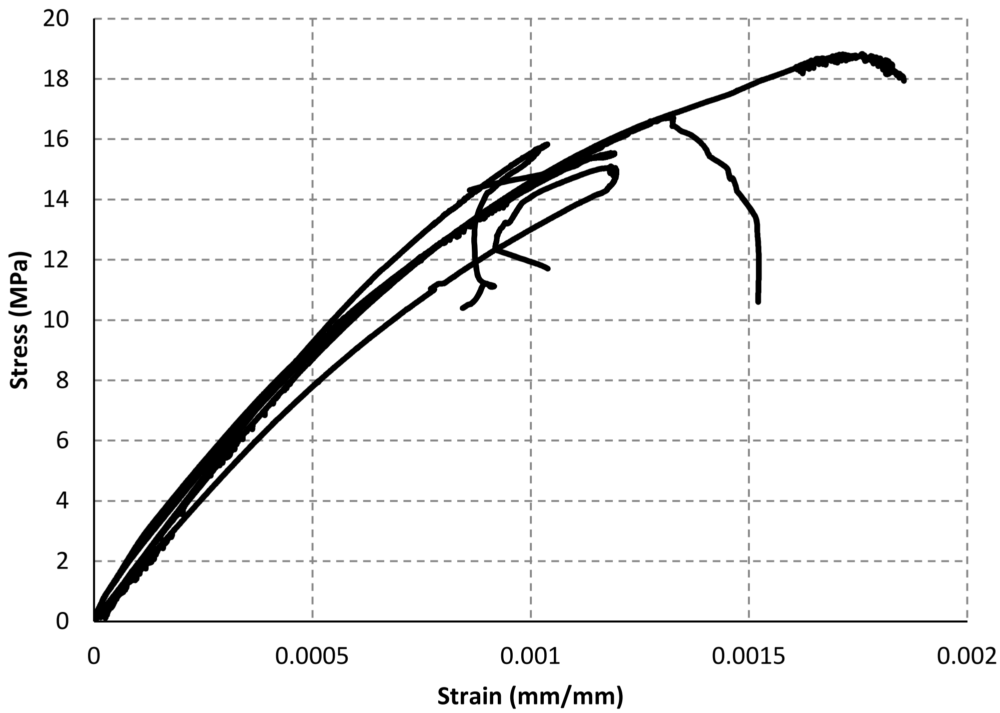



**Figure C-9: Stress Strain Curves for 20-MC-N Prisms**

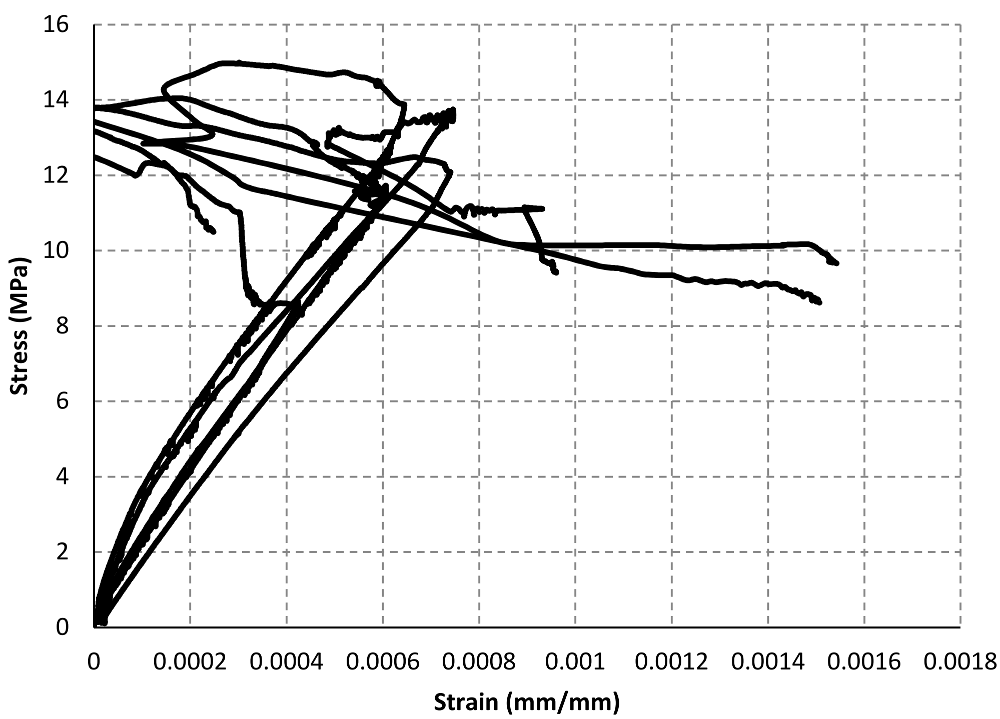



**Figure C-10: Stress-Strain Curves for 20-MC-S Prisms**

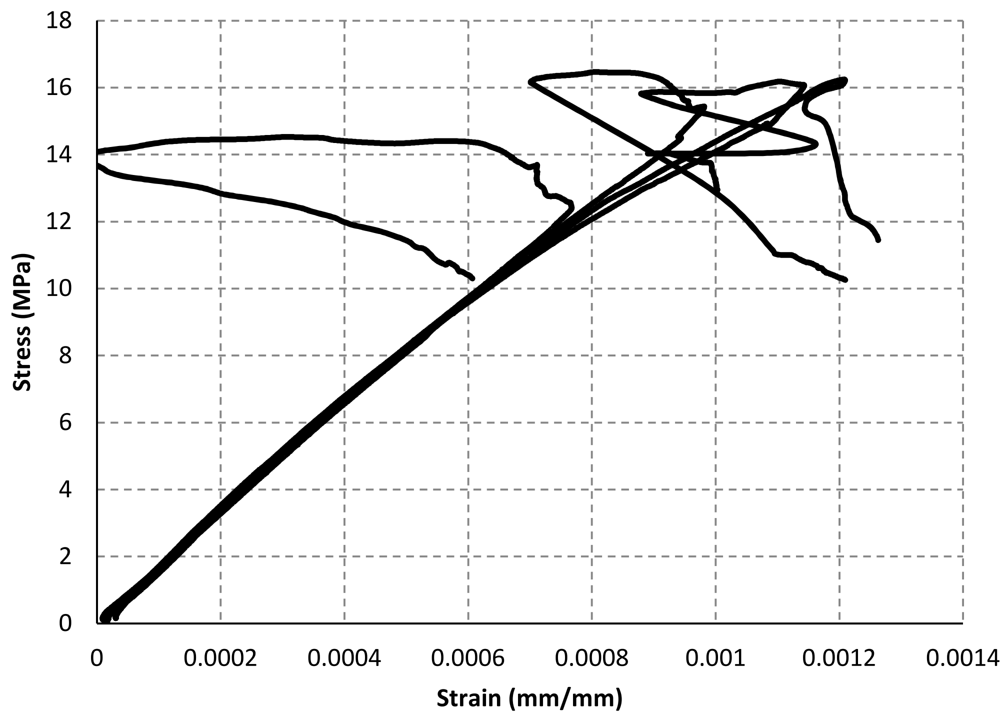



**Figure C-11: Stress-Strain Curves for 20-PCL-N Prisms**

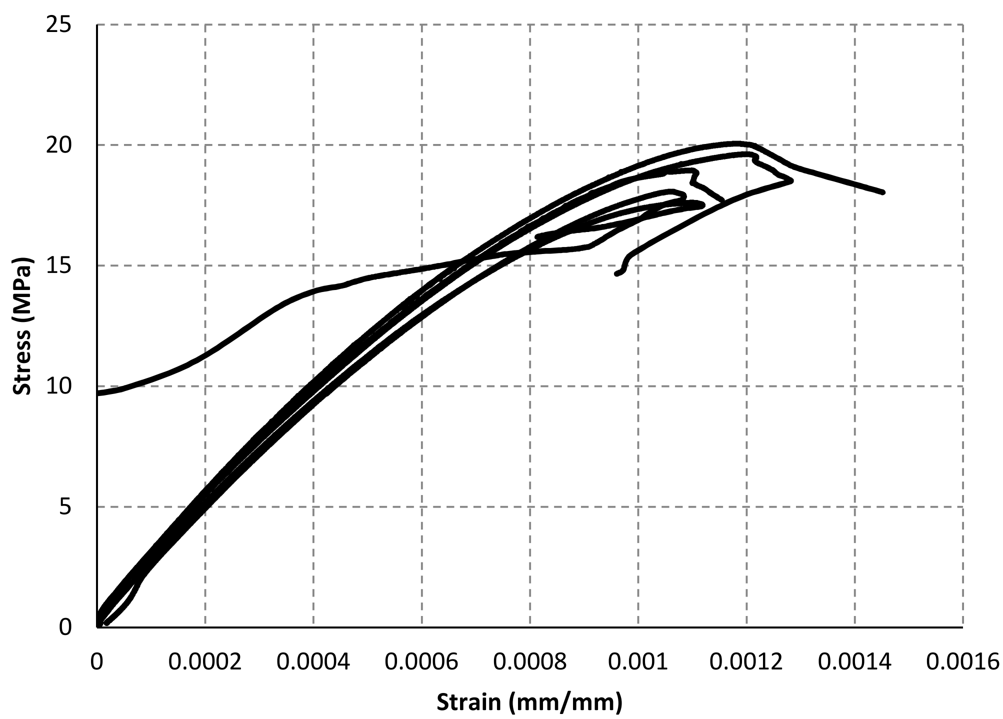



**Figure C-12: Stress-Strain Curves for 20-PCL-S Prisms**

**Table C-4: Individual Prism Results for Prisms with 30 MPa Units**

| Prism Designation | Compressive Strength | | | | | Young's Modulus | | |
|---|---|---|---|---|---|---|---|---|
| | Per Prism (MPa) | Adjusted* (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Prism (GPa) | Average Modulus (GPa) | COV (%) |
| 30-MC-N | 16.17 | 14.55 | 14.85 | 2.23 | 12.42 | 24.77 | 22.24 | 9.55 |
| | 16.25 | 14.62 | | | | 23.58 | | |
| | 16.37 | 14.73 | | | | 20.48 | | |
| | 16.66 | 14.99 | | | | 19.68 | | |
| | 17.07 | 15.37 | | | | 22.67 | | |
| 30-MC-S | 13.35 | 12.01 | 13.05 | 5.72 | 10.91 | 21.66 | 23.40 | 7.58 |
| | 14.16 | 12.74 | | | | 24.14 | | |
| | 14.67 | 13.20 | | | | 22.92 | | |
| | 15.61 | 14.05 | | | | 26.10 | | |
| | 14.70 | 13.23 | | | | 22.19 | | |
| 30-PCL-N | 18.56 | 16.71 | 16.52 | 10.66 | 13.63 | 20.73 | 21.71 | 11.75 |
| | 16.74 | 15.07 | | | | 19.19 | | |
| | 16.10 | 14.49 | | | | 22.57 | | |
| | 20.85 | 18.77 | | | | 20.34 | | |
| | 19.51 | 17.56 | | | | 25.72 | | |
| 30-PCL-S | 18.31 | 16.48 | 16.02 | 14.20 | 12.29 | 38.28 | 34.71 | 13.11 |
| | 19.79 | 17.81 | | | | 33.36 | | |
| | 13.47 | 12.12 | | | | 28.48 | | |
| | 18.08 | 16.27 | | | | 33.44 | | |
| | 19.37 | 17.44 | | | | 40.00 | | |

*Adjusted: Maximum stress factored by 0.9 to account for height-to-thickness effects.

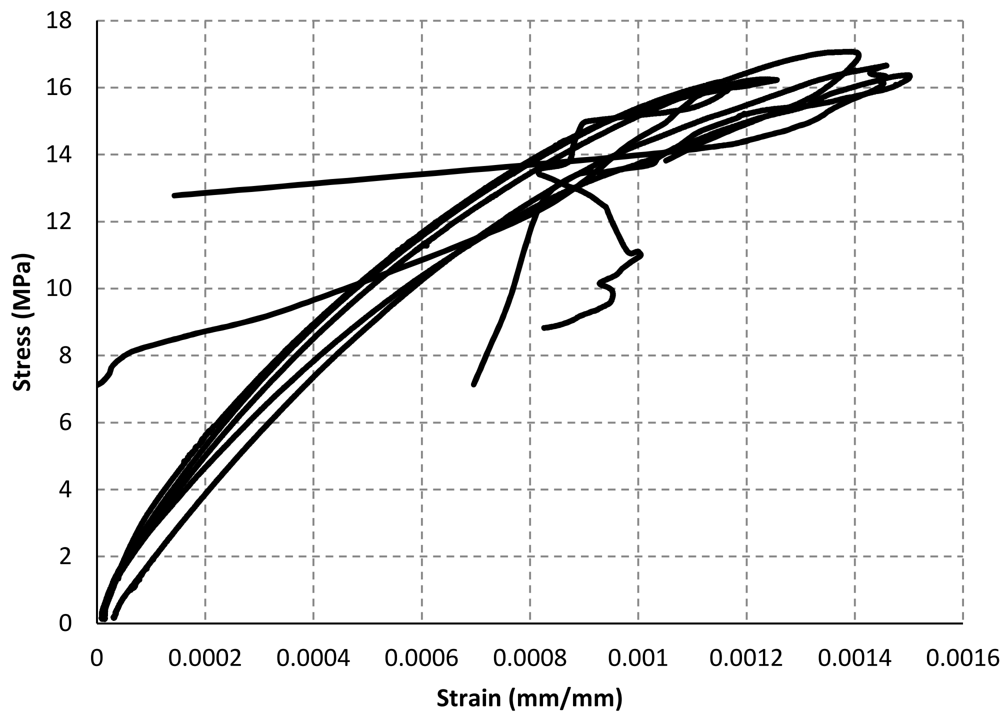



**Figure C-13: Stress-Strain Curves for 30-MC-N Prisms**

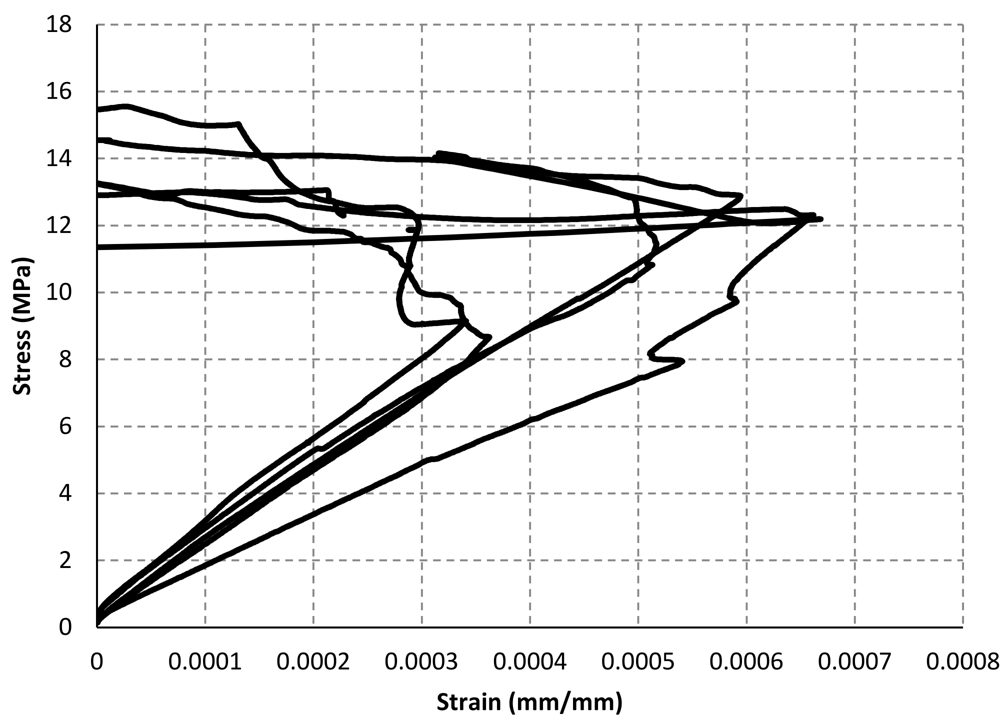



**Figure C-14: Stress-Strain Curves for 30-MC-S Prisms**

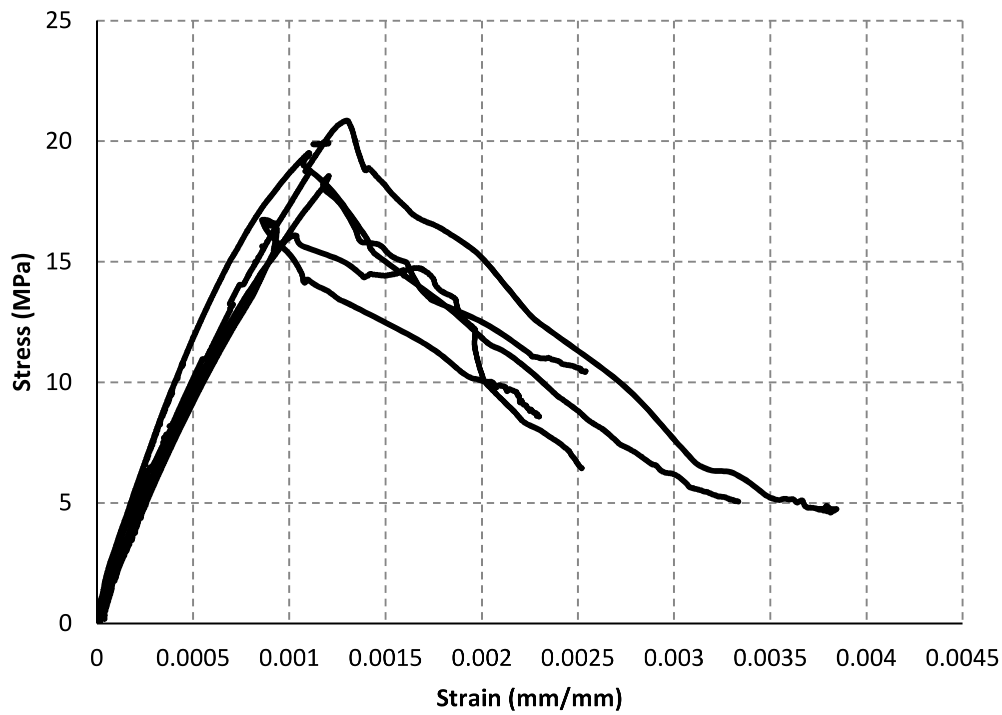



**Figure C-15: Stress-Strain Curves for 30-PCL-N Prisms**

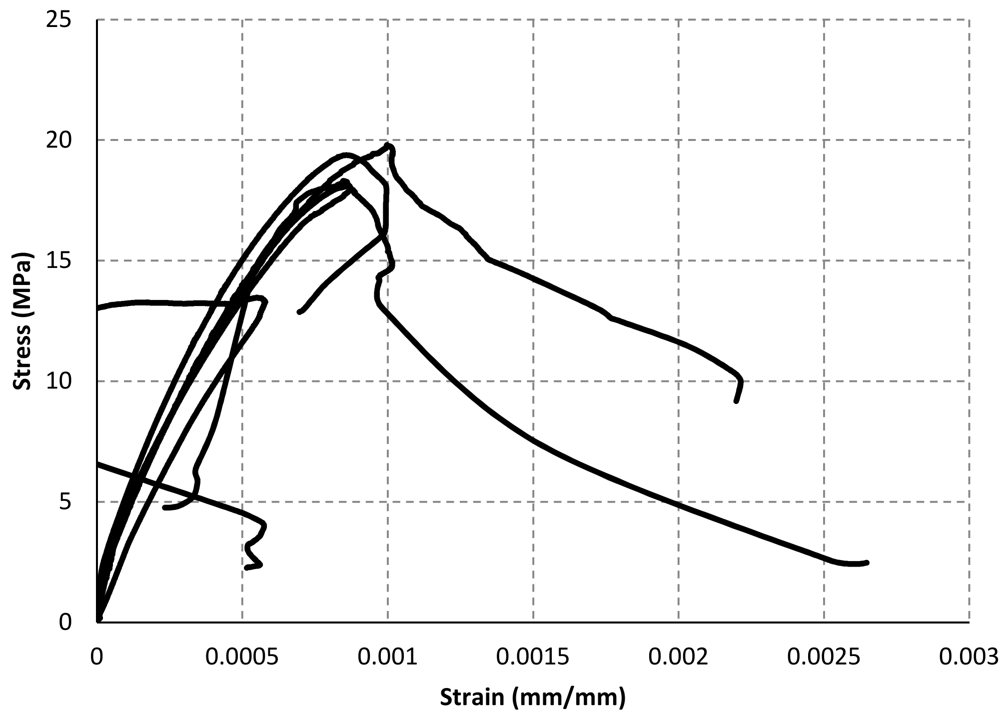



**Figure C-16: Stress-Strain Curves for 30-PCL-S Prisms**

**Table C-5: Individual Prism Results for Prisms with 40 MPa Units**

| Prism Designation | Compressive Strength | | | | | Young's Modulus | | |
|---|---|---|---|---|---|---|---|---|
| | Per Prism (MPa) | Adjusted* (MPa) | Average (MPa) | COV (%) | Specified (MPa) | Per Prism (GPa) | Average Modulus (GPa) | COV (%) |
| 40-MC-N | 16.54 | 14.89 | 13.66 | 8.40 | 11.42 | 24.00 | 23.27 | 8.33 |
| | 14.57 | 13.12 | | | | 23.31 | | |
| | 14.18 | 12.76 | | | | 23.76 | | |
| | 14.03 | 12.63 | | | | 20.04 | | |
| | 16.57 | 14.92 | | | | 25.22 | | |
| 40-MC-S | 22.13 | 19.91 | 19.17 | 10.43 | 15.89 | 34.12 | 29.64 | 8.60 |
| | 20.39 | 18.35 | | | | 28.90 | | |
| | 24.80 | 22.32 | | | | 28.10 | | |
| | 19.71 | 17.74 | | | | 28.01 | | |
| | 19.45 | 17.50 | | | | 29.06 | | |
| 40-PCL-N | 19.03 | 17.13 | 19.15 | 8.07 | 16.01 | 23.02 | 24.62 | 10.32 |
| | 22.92 | 20.63 | | | | 23.89 | | |
| | 21.91 | 19.74 | | | | 27.45 | | |
| | 22.62 | 20.35 | | | | 21.67 | | |
| | 19.91 | 17.92 | | | | 27.07 | | |
| 40-PCL-S | 20.56 | 18.51 | 17.58 | 5.24 | 14.70 | 30.47 | 31.36 | 6.13 |
| | 20.20 | 18.18 | | | | 32.85 | | |
| | 19.34 | 17.40 | | | | 28.94 | | |
| | 17.91 | 16.12 | | | | 30.81 | | |
| | 19.67 | 17.70 | | | | 33.74 | | |

*Adjusted: Maximum stress factored by 0.9 to account for height-to-thickness effects.

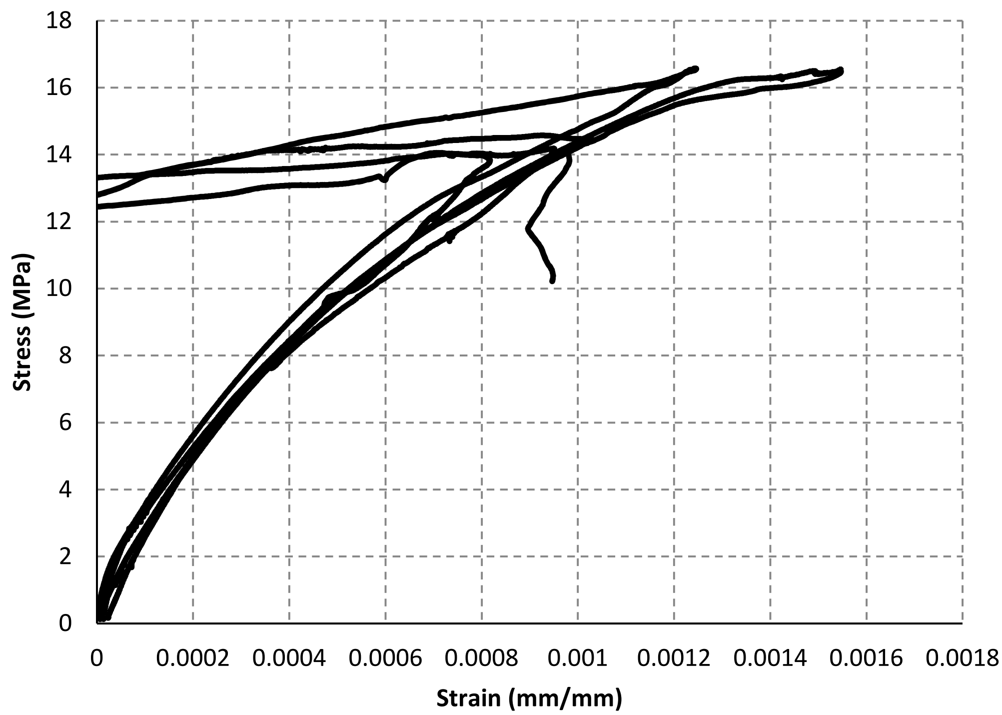



**Figure C-17: Stress-Strain Curves for 40-MC-N Prisms**

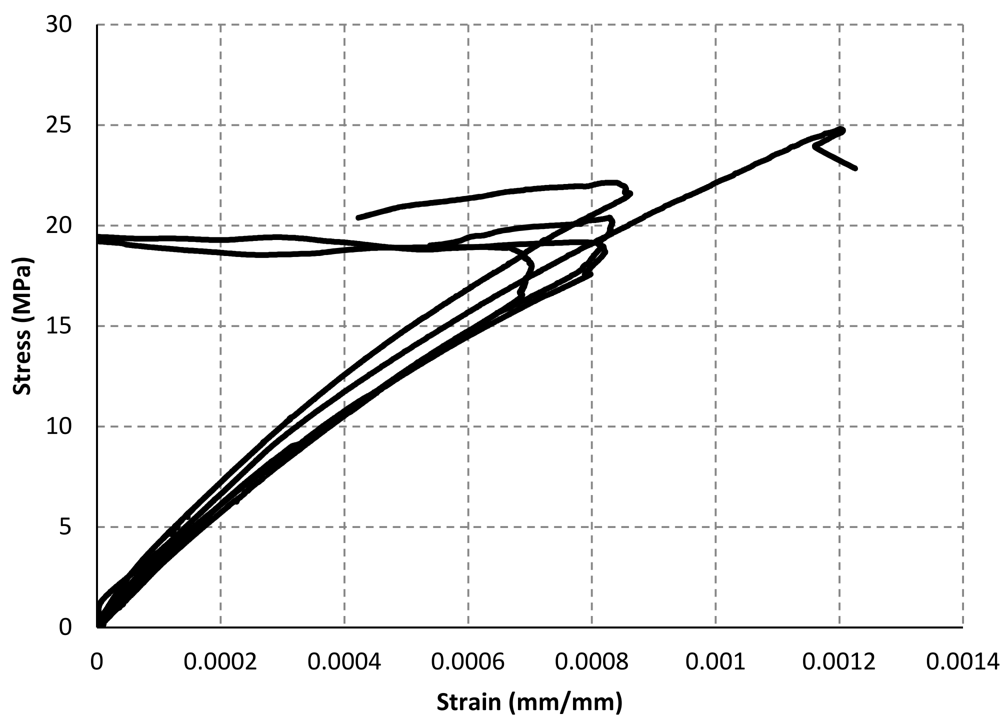



**Figure C-18: Stress-Strain Curves for 40-MC-S Prisms**

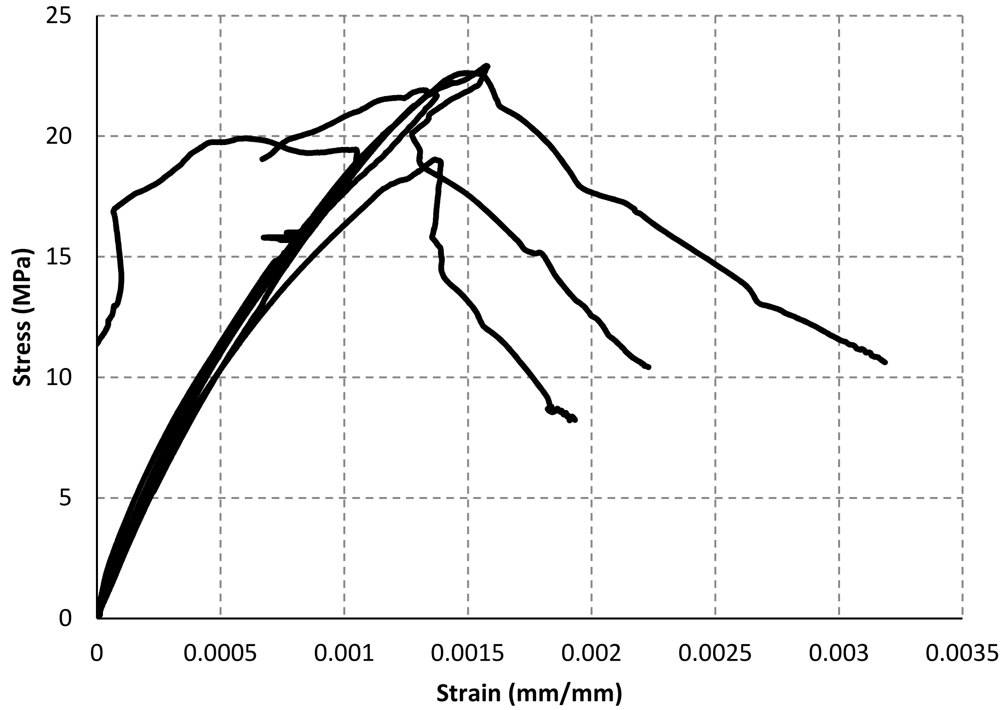



**Figure C-19: Stress-Strain Curves for 40-PCL-N Prisms**

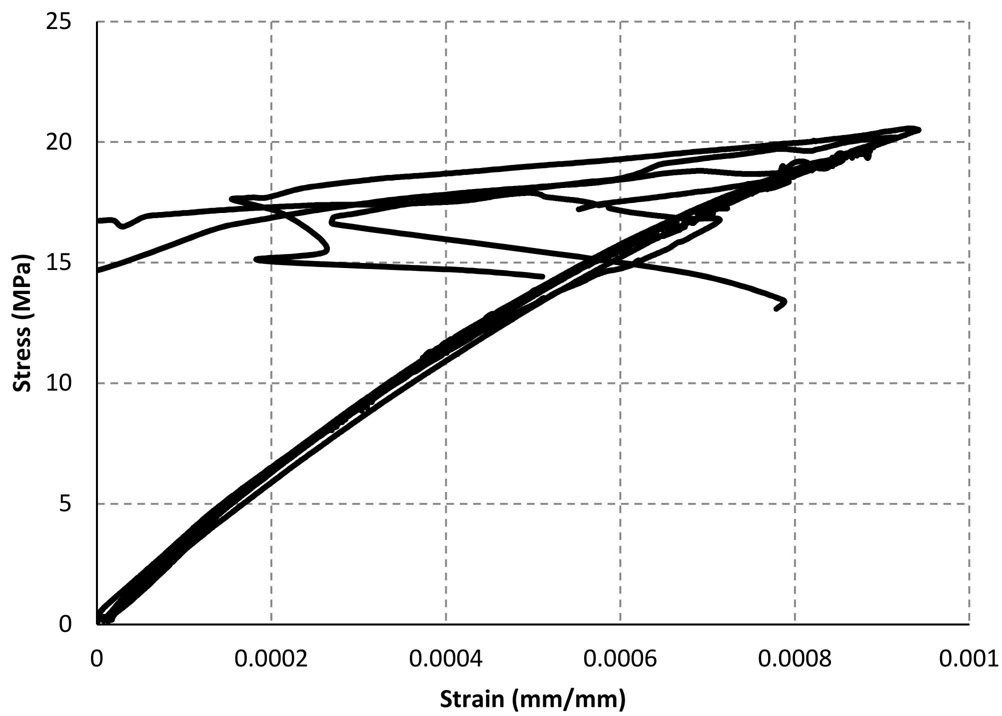



**Figure C-20: Stress-Strain Curves for 40-PCL-S Prisms**