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PROPERTIES OF GROUT UNDER UNIAXIAL AND TRIAXIAL COMPRESSION

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ABSTRACT

A total of 166 grout specimens made using 4 types of moulds were tested in uniaxial and triaxial compression. Five lateral confining pressures ranging from 0 to 14 MPa (2 ksi) were applied to weak, medium and strong grout specimens. Both static and cyclic loading tests were carried out. High confining pressure was found to increase significantly both the ultimate strength and ductility of all the types of grout.

INTRODUCTION

Stimulated by the rapid development of computer engineering, researchers have become much more interested in the investigation and modelling of the fundamental mechanical properties of engineering materials. Unfortunately, many of the existing test methods for the constituent masonry materials are suitable only for quality control. As a result, the true mechanical properties of masonry materials have not been well defined.

A systematic investigation into the true mechanical properties of various blocks, mortars and grouts in uniaxial compression, tension and triaxial compression has been carried out to lay a sound foundation for further investigation and numerical modelling of masonry (Guo 1991). In this paper, the properties of 166 grout specimens made using 4 types of moulds and tested under 5 different lateral confining pressures are reported.

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EXPERIMENTAL PROGRAM

Test Method

Background. According to ASTM Standard E 447 (ASTM 1990), a minimum of three 50 mm (2 in.) cubes for fine grout or 75x150 mm (3x6 in.) cylinders for coarse grout, cast in nonabsorbent moulds and moist cured for 48 hours, are used as the standard test specimens. On the other hand, CSA Standard CAN3-A369.1-M84 (CSA 1984), similar to ASTM Standard C 1019 (ASTM 1990), requires that the test specimen for grout be a minimum of six 75x75x150 mm (3x3x6 in.) prisms moulded by masonry units and moist cured. These standards have been generally followed by masonry researchers except that specimens with slightly different dimensions and air curing condition have also been used (i.e., Cheema 1981 and Hamid 1978).

It is well known that masonry units will absorb water from the fresh grout and thus change its properties. Therefore, use of the nonabsorbent mould specified in ASTM Standard E 447 does not produce test specimens which represent the grout in masonry structures. It is true that the mould adapted by CSA Standard CAN3-A369.1-M84 and ASTM Standard C 1019 can absorb water from the fresh grout, but they still may not produce specimens which closely represent the grout in masonry structures for the following three reasons:

1. The volume to surface ratio of the specimen may be quite different from that of the grout in masonry structures.
2. The distribution of the absorbent masonry unit material around the grout specimen is different from that in masonry structures.
3. The moist curing condition is quite different from what the grout experiences in masonry structures.

Method Used. To obtain the true properties of the grout in masonry structures, the key point is to ensure that the water/cement ratio in the test specimen is the same as in the masonry structures. An accurate and also quite simple approach is to cut or drill the test specimens out of the grouted cells which were cast using the same methods and materials as used in masonry structures.

Scope of Investigation

Grout Types. Three types of grouts, labelled as weak, medium and strong, were investigated in this study. Their mixes are shown in Table 1 and the water was added to give about a 180 mm (7 in.) slump. Most of the grout specimens were air cured in the laboratory but some triaxial compression grout specimens were water cured which will be identified later. The sieve analysis results for the local sands used to make the grout are provided in Table 2. The coarse aggregate was pea gravel with a maximum diameter of 6 mm (0.25 in.).

Table 1. Grout Mixes

Grout Type	Proportions by Volume (Weight)				
	Porland Cement	Hydrated Lime	Concrete Sand	Gravel	Water
Weak	1		5(5.95)		(1.10)
Medium	1	0.1(0.044)	3(3.22)		(0.51)
Strong	1		1(1.11)	1(0.9)	(0.36)

Table 2. Sieve Analysis Results for Sand

Sieve Size (mm)	Percent Passing		
	Concrete Sand	Masonry Sand	CSA A82.56-M1976
5	98.6	99.9	100
2.5	88.1	99.5	95-100
1.25	78.7	96.6	60-100
0.630	50.4	84.5	35-80
0.315	9.6	38.0	15-50

Mould Types. Four types of moulds, labelled as block, blocks, metal and plastic, were used to make grout specimens. Specimens made using block moulds were cut or drilled out from the centre of the grouted cells in a 20 cm standard hollow concrete block. The mould type labelled as blocks were similar to that specified in CSA Standard CAN3-A369.1-M84 except that the specified bottom wooden block was omitted and the specimen was later saw cut to the required height. The cut-off portion provided a grout plate which was used as a splitting tensile specimen as reported elsewhere (Guo 1991). The metal or plastic mould was a nonabsorbent mould as specified in ASTM Standard E 447.

Specimen Types. Both grout prisms and cylinders were tested. The dimensions of the grout prisms were 75×75×150 mm (3×3×6 in.), the same as specified in CSA Standard CAN3-A369.1-M84. The diameters of the cylinder specimens were 50 mm, 75 mm, 100 mm or 200 mm. The cylinder specimen height was maintained at twice the specimen diameter.

Loading Conditions. Most of the grout specimens were tested under static load, with the load gradually increased until failure. However, to gain some insight into the influence of loading history on the compression behaviour of grout, some grout specimens were tested under cyclic load. Five cycles of loading were used at each load level which was increased in increments of 20% of the static capacity starting at 30%. Both uniaxial compression and triaxial compression tests were conducted. The uniaxial compression tests were used to investigate the influence of grout types, mould types, bearing platen types and specimen dimensions on the fundamental mechanical properties of grout under compression. The triaxial compression tests were used to obtain more advanced grout properties under three dimensional stress states. A total of 5 different lateral confining pressures ranging from 0 to 14 MPa (2 ksi) were used in this study.

Test Procedure

Uniaxial Compression. All grout specimens were capped using sulphur at least 24 hours before the test. To provide uniform distribution of stress and strain in the whole specimen and to check whether the platen restraint effect would affect the ultimate strength, specimens were tested between both the steel brush platens (Guo et. al. 1989) and solid steel plates. Two LPDTs (Linear Potential Displacement Transducer) were glued on the specimen to measure the vertical deformations on opposite faces. Another 2 LPDTs were used to measure the horizontal deformations on the other two sides. The overall vertical deformation was also measured by 4 LPDTs each located close to a corner of the grout prism. All the deformation and load outputs were fed into a computer controlled Optilog data acquisition system. This system made it possible to quickly sample (40 channels per second) and record load and deformations, while not interrupting the loading process.

Triaxial Compression. The two ends of all the triaxial test specimens were sulphur capped at least 24 hours before the test. A thin layer of epoxy resin was also coated on the specimen side surface at strain gauge locations at least 24 hours before mounting the strain gages. The vertical and lateral deformations were measured using four 30 mm (1.2 in.) long foil strain gages mounted diametrically on at least one specimen for every lateral confining pressure and grout type. Each specimen was then waterproofed using a 0.3 mm (0.01 in.) thick latex membrane. To prevent the membrane from being broken after the specimen cracked, a 0.9 mm (0.035 in.) thick rubber sheet was added between the specimen and the latex membrane. Dow Corning, a type of high vacuum grease, was applied at the small overlapping region of the rubber sheet to prevent the rubber sheet from restraining the lateral expansion of the specimen.

The cylinders were tested in the high pressure triaxial cell WF40020 for lateral pressure up to 14 MPa (2 ksi). During each test, the lateral pressure was first applied to the desired level, and then the vertical load was supplemented by a MTS test machine under displacement control at a rate of 0.01 mm/sec (0.004 in/sec), while the lateral pressure was kept constant. Overall vertical displacements were measured for every specimen using the built-in LVDT (Linear Variable Differential Transducer) of the MTS test machine. All the deformation and load outputs were fed into the computer controlled Optilog data acquisition system.

TEST RESULTS AND DISCUSSIONS

Uniaxial Compression

Failure Mode. Typical failures under uniaxial compression are shown in Fig. 1 for grout prisms. When tested between solid bearing plates, a typical conical failure developed due to the end platen restraint effect. When tested between the brush platens, however, vertical cracks usually extended through the whole height of the specimen, indicating the elimination of the end platen restraint.

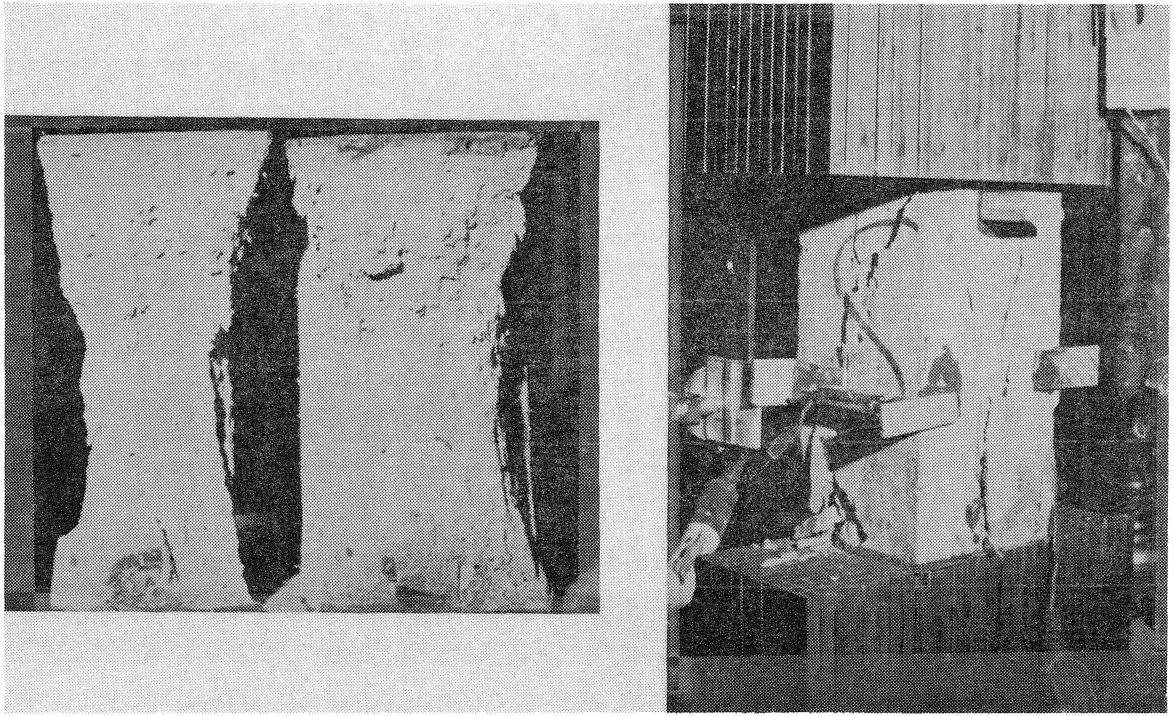
Strength. Uniaxial compression strengths for all of the specimens are summarized in Table 3. Comparison of the test results of Series 1 and 2 to those for Series 3 and 4 shows that, for weak grout, the specimens cast in the CSA Standard mould (i.e., blocks) are stronger than those cut out of the grouted block cells. This may be attributed to the CSA Standard mould being able to absorb more water from the fresh weak grout than the latter. Conversely, for the medium and strong grout specimens, the strengths of specimens cast in the CSA Standard mould are slightly lower than for specimens cut out of the grouted block cells (Series 9 and 10 versus 11 and 12 and Series 17 and 18 versus 19 and 20). This may indicate that it is not beneficial to the compressive strength of grout to take too much water out of the medium and strong grouts where, as shown in Table 1, the water/cement ratios are much smaller than for the weak grout and, for dry curing conditions, hydration of the cement may be reduced.

The strengths of the specimens cast in the nonabsorbent mould specified in ASTM Standard E 447 are generally the lowest compared to the other corresponding specimens.

The last column of Table 3 shows the strength ratios of specimens tested between solid bearing plates compared to similar specimens tested between the brush platens. These ratios, all being greater than 1.0, indicate that some end platen restraint still existed in the specimens. Due to the small number of the specimens tested, however, most of the mean strength differences are not statistically significant at the 95% confidence level.

Stress-Strain Curve. Typical stress-strain curves for specimens cut out of the grouted block cells and tested between brush platens are presented in Fig. 2. The stress-strain relationships for all types of grout are not linear and exhibit well defined ascending and descending branches. For the ascending branch, the tangent modulus gradually decreases at an increasing rate, and becomes zero at the peak stress. For the descending branch, the tangent modulus becomes negative with the absolute value increasing very quickly at first but gradually becoming smaller later (i.e., a point of inflection exists). All of these results are similar to results reported for the hollow concrete blocks tested in compression (Guo et. al. 1989).

The curves in Fig. 2 also indicate that weaker grout is more ductile than stronger grout. This is consistent with the observation that failure was quite sudden for strong grout specimens whereas weak grout specimens sustained the peak load for a while before the load gradually decreased.



(a) Solid Steel Plates (b) Steel Brush Platens

Fig. 1 Typical Failures for Grout Prisms Tested under Uniaxial Compression

Table 3. Summary of Uniaxial Compression Test Results for Grout

Series #	Grout Type	Mould Type	Specimen Dimensions (mm)	Bearing Platens	Number of Tests	Mean Strength (MPa)	C.O.V. (%)	Solid Plate / Brush Platen
1	Weak	Block	75×75×150	Solid	3	12.3	2.7	1.12
2	Weak	Block	75×75×150	Brush	3	11.0	11.1	
3	Weak	Blocks	75×75×150	Solid	3	17.1	10.7	1.10
4	Weak	Blocks	75×75×150	Brush	3	15.5	1.9	
5	Weak	Metal	100ϕ×200	Solid	3	12.3	1.5	
6	Weak	Metal	75ϕ×150	Solid	3	10.3	3.8	1.07
7	Weak	Metal	75ϕ×150	Brush	3	9.6	5.5	
8	Weak	Block	50ϕ×100	Brush	6	14.3	10.0	
9	Medium	Block	75×75×150	Solid	3	45.9	6.3	1.14
10	Medium	Block	75×75×150	Brush	3	40.2	3.7	
11	Medium	Blocks	75×75×150	Solid	3	39.8	3.1	1.15
12	Medium	Blocks	75×75×150	Brush	3	34.6	10.0	
13	Medium	Metal	100ϕ×200	Solid	3	35.1	6.3	
14	Medium	Metal	75ϕ×150	Solid	3	33.2	4.6	1.26
15	Medium	Metal	75ϕ×150	Brush	3	26.4	4.5	
16	Medium	Block	50ϕ×100	Brush	6	43.6	9.2	
17	Strong	Block	75×75×150	Solid	3	61.8	2.0	1.10
18	Strong	Block	75×75×150	Brush	3	55.9	6.1	
19	Strong	Blocks	75×75×150	Solid	3	63.0	2.0	1.26
20	Strong	Blocks	75×75×150	Brush	3	50.2	0.8	
21	Strong	Metal	100ϕ×200	Solid	3	54.5	1.8	
22	Strong	Metal	75ϕ×150	Solid	3	52.0	1.4	1.27
23	Strong	Metal	75ϕ×150	Brush	3	40.8	11.4	
24	Strong	Block	50ϕ×100	Brush	6	54.3	6.3	

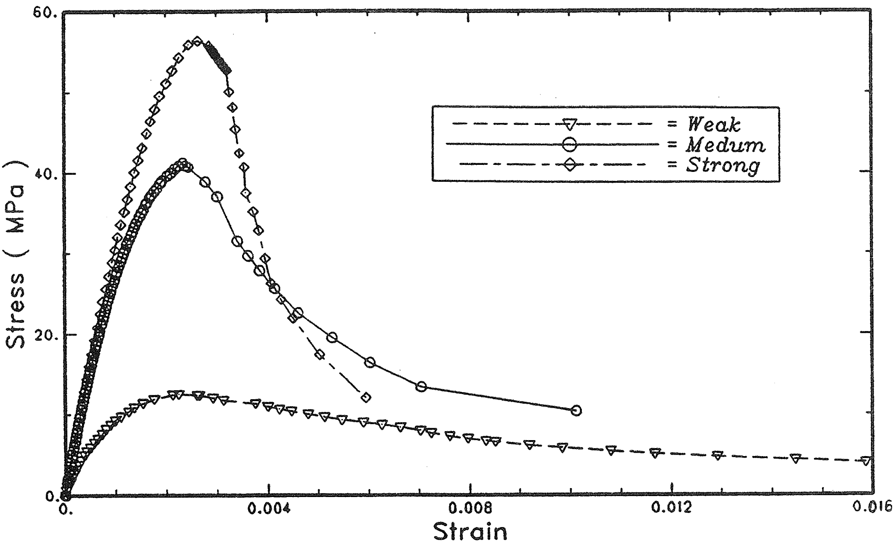


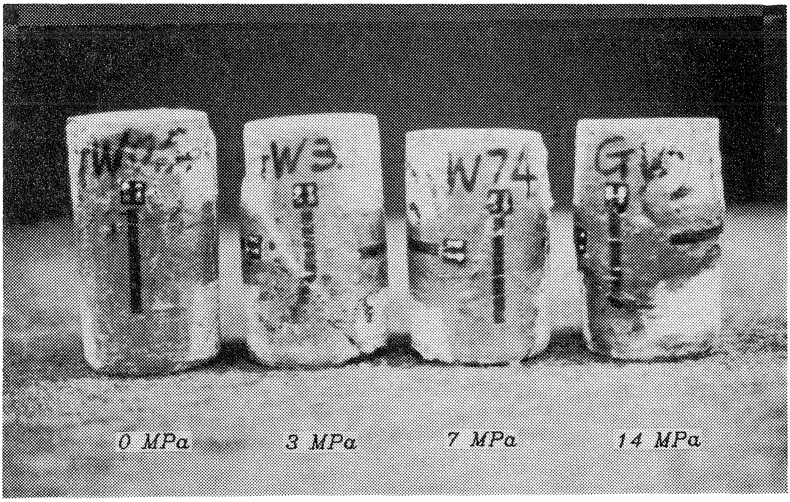
Fig. 2 Typical Stress-Strain Curves for Grout Specimens Cut from Grouted Cells and Tested under Uniaxial Compression using Brush Platens

Triaxial Compression

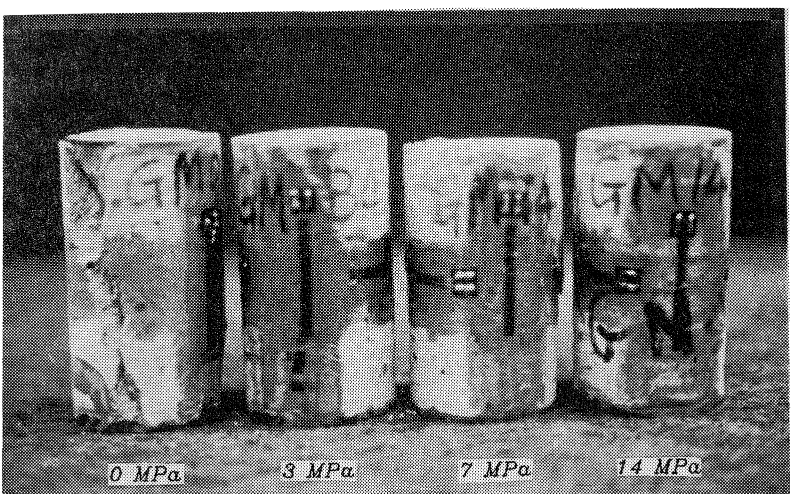
Failure Mode. Typical failures of weak and medium strength grout specimens tested under different lateral confining pressures are shown in Fig. 3. The failure of strong grout is not included in Fig. 3 because the specimen generally broke into loose pieces after the test. The failure modes shown in Fig. 3 suggest that the relatively brittle grout can exhibit very ductile behaviour under high confining pressures especially for the weak grout. That is, the type of splitting cracks typical for zero confining pressure were not evident under high confining pressure.

Although the weak grout specimens sustained much larger vertical strains than the medium grout specimens, their cracks were similar or even less evident. This indicates that the damage to specimens depends mainly on the ratio of the confining pressure to the unconfined compressive strength and not solely on the magnitude of the confining pressure.

Strength. The triaxial compression strengths of the grout specimens are summarized in Table 4. The use of a lower maximum lateral confining pressure for the strong grout specimens, compared to the weak and medium grouts, was necessitated by the limitation of the test machine capacity.



(a) Weak Grout



(b) Medium Grout

Fig. 3 Typical Triaxial Compression Failures for Grout Specimens Tested under Different Lateral Confining Pressures

Table 4. Summary of the Triaxial Test Results for Grout

Series Number	Grout Type	Mould Type	Lateral Pressure (MPa)	Loading Type	Number of Tests	Mean Axial Strength (MPa)	C.O.V. (%)
1	Weak	Block	0	Static	6	14.3	13.0
2	Weak	Block	3	Static	4	24.4	3.9
3	Weak	Block	7	Static	4	39.6	6.3
4	Weak	Block	14	Static	4	62.9	11.7
5	Medium	Block	0	Static	5	41.2	10.1
6	Medium	Plastic	0	Static	3	46.9	11.4
7	Medium	Block	3	Static	4	58.2	11.7
8	Medium	Block	3	Cyclic	4	64.3	6.4
9	Medium	Block	7	Static	4	71.1	4.3
10	Medium	Block	7	Cyclic	3	84.9	8.9
11	Medium	Plastic	7	Static	3	78.8	2.9
12	Medium	Block	14	Static	5	94.1	7.9
13	Medium	Block	14	Cyclic	3	95.4	7.8
14	Medium	Plastic	14	Static	3	99.7	1.5
15	Strong	Block	0	Static	6	63.0	13.5
16	Strong	Block	3	Static	5	82.9	8.5
17	Strong	Block	3	Cyclic	3	82.8	7.1
18	Strong	Block	7	Static	5	101.9	2.0
19	Strong	Block	7	Cyclic	3	104.4	1.9
20	Strong	Block	10	Static	5	114.3	7.3
21	Strong	Block	10	Cyclic	3	114.4	5.5

The test results in Table 4 clearly demonstrate that increasing the confining pressure can significantly increase the axial compression strength of grout.

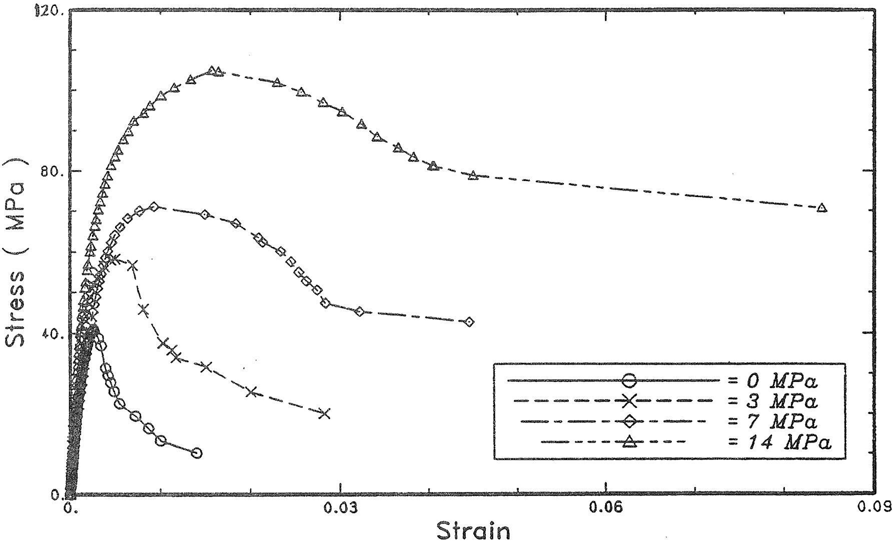


Fig. 4 Typical Triaxial Compression Stress-Strain Curves for Medium Grout Tested under Different Lateral Confining Pressures

The specimens in Series 6, 11 and 14 were cast in nonabsorbent hard plastic tubes and were cured in water. These specimens had higher strengths than corresponding air cured specimens (Series 5, 9 and 12, respectively) cut out of the grouted block cells. This result is consistent with uniaxial tests where too little water remained for rapid hydration of the block moulded specimen.

Stress-Strain Curve. Typical stress-strain curves for the medium grout under various lateral confining pressures are shown in Fig. 4. Obviously, increased confining pressure also dramatically increased the ductility of the grout. Similar to the stress-strain curves under uniaxial compression, the stress-strain curves for all of the grout types under triaxial compression still had well defined ascending and descending branches, with higher axial compressive strengths at larger strains. However, the descending branches for the weak grout were much flatter than those for the strong grout.

The test results suggest that the enhancement of axial compressive strength and ductility due to the lateral confining pressure depend mainly on the ratio of the confining pressure to the unconfined ultimate strength, not solely on the magnitude of the confining pressure.

CONCLUSIONS

The following major conclusions can be drawn from this investigation:

1. Specimens cut or drilled from grouted cells of blocks are more representative of the grout in masonry structures than the specimens specified in ASTM Standard C 1019, ASTM Standard E 447 or CSA Standard CAN3-A369.1-M84.

2. The stress-strain relationships for grout under both uniaxial and triaxial compression are smooth curves consisting of ascending and descending branches.

3. Lateral confining pressure can significantly increase both the axial compressive strength and ductility of grout. This enhancement depends mainly on the ratio of the confining pressure to the uniaxial compressive strength of grout, not solely on the magnitude of the confining pressure.

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