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RESEARCH PAPERS

Pullout resistance of anchor bolts: Effect of matrix properties

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ABSTRACT

The effect of sand grain size on anchor bolt pullout resistance from a cementious matrix was investigated. Two different kinds of cement mortars were examined: an ordinary Portland cement and a quick-setting acid-base wollastonite phosphate cement mortar. The pullout resistance of (M8) threaded anchor bolts was evaluated. The Scanning Electron Microscope (SEM) was used to capture images of the microstructure of the bolt/matrix interface. It was found that the pullout shear strength was higher in Portland cement compared to wollastonite mortar, and increased with increasing grain size. The influence of change of grain size was less significant in wollastonite mortar. These trends can be explained on the basis of the aggregate-cement bond properties of each cement system, the roughness of the matrix at the shear interface zone, the penetration of matrix in between the bolt threads and the matrix properties.

1. INTRODUCTION

Anchors are used in a variety of fastening applications such as repair of concrete, masonry materials, and precast concrete construction [1]. Grouted rock anchors are also used extensively in a wide range of geotechnical and mining applications [2].

Anchors are often inserted in a drilled hole, in which a grout or cement-based mortar is subsequently injected. In these applications, a fast setting cement-based mortar is desirable. There is a broad variety of fast setting cement materials which can be potentially used, such as hydraulic cements and acid based cements. Although Portland cement is in common use, fast-setting acid based cements are more effective if rapid development of strength is required. For example, acid-based wollastonite cement [3], a crystalline calcium monosilicate (CaO SiO_2), is a low cost cement, that is found naturally in large quantities around the world and it is used in many building material applications.

Using Portland cement and wollastonite, the effect of sand grain size on bond with adhesive anchors was studied. The nature of the load transfer between adhesive anchors and the mortar depends primarily on the anchor/mortar interfacial properties, *i.e.* anchor surface type and characteristics of the mortar. The mortar has to provide adequate interfacial bonding and anchoring capacity. Both bonding and anchoring capacity can be enhanced by the introduction of sand to the mortar [2].

An overview of chemically bonded anchors is given by Cook [4], where the failure modes of this type of anchor is outlined. A fracture mechanics based stress analysis and numerical modeling of the rod pullout problem is provided by Atkinson [5]. In the current study, tests on pullout specimens were carried out where the bolt is pulled through a bearing plate. Studies on the shear stress distribution in pullout specimens with such boundary conditions in such specimens has been published by Perry [6].

2 EXPERIMENTAL PROGRAM

2.1 Materials

Type I Portland cement, and an acid-based wollastonite cement reacting with a phosphate solution (see Table 1) were used for comparision. Both Portland cement and wollastonite cement are mixed with four dif-

Table 1 – Composition of phosphate solution [7]

Phosphoric acid 85% (H_3PO_4) [g]	Aluminium phosphate ($AlPO_4$) [g]	Deionized water (H_2O) [g]	Zinc phosphate ($Zn_3(PO_4)_2*xH_2O$) [g]	Magnesium phosphate hydrate $Mg_3(PO_4)_2*xH_2O$) [g]
57.5	11.5	20.5	10.0	0.5

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Table 2 – Mortar mix proportions (by weight)		
	Liquid/cement ratio	Sand/cement ratio
Portland cement	0.5	1.0
Wollastonite	0.9	1.0

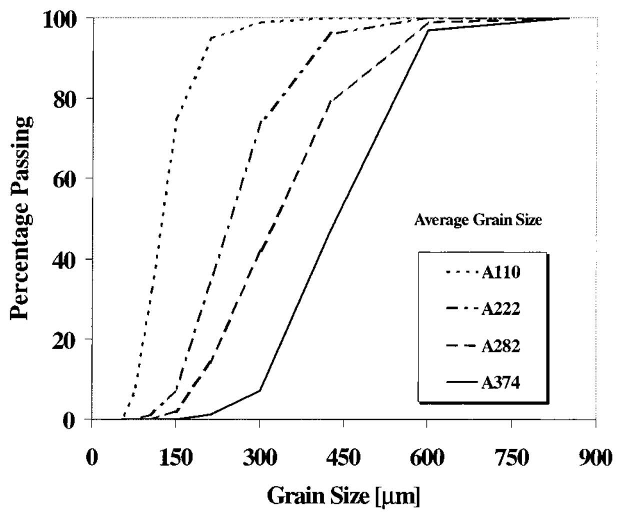


Fig. 1 – Sand grading curve and average grain size.

ferent grain sizes of silica sand. The mix proportions are presented in Table 2; the sand distribution and the average grain size for each sand type are presented in Fig. 1.

2.2 Specimen preparation

PVC pipes with 26 mm inside diameter and 50 mm length were used as molds for casting the pullout specimens. The same PVC pipes were also used to cast the compression cylinders in order to characterize the mortar material. The pulled out bolts were all threaded (M8) anchor bolts.

Pullout specimens: Four sand grain sizes were examined in pullout for the two mortar systems. The preparation of the pulled out specimens was as follow: first the anchor bolt was fixed in the center of the mold along the pipe axis, *i.e.* parallel to the direction of the pullout load. The entire mold length (50 mm) was used as the embedding length of the anchor bolt. Then the mortar mixture was poured inside the mold around the bolt. The specimen was vibrated in order to achieve a good distribution of mortar around the bolt. The specimens were cured and tested with the molds.

Compression specimens: Two sand sizes were examined in compression, A110 and A374, for both mortar systems. The mortar mixtures were poured inside the mold and after 24 hours removed from the mold and cured until testing.

2.3 Curing

Upon casting, all Portland cement specimens were covered with a thin sheet of plastic to minimize evaporation losses. After 24 hours all specimens were cured for 28 days at 100% humidity in 27ºC, and thereafter held in an environmental chamber at 50% humidity and 22ºC until testing. Pullout tests were performed 40 days after casting and compression tests were conducted 16 days after casting. The wollastonite specimens were kept at room temperatures for 3 days prior to testing. It is important to note that the wollastonite specimens set approximately 10 minutes from the time of casting.

3. TESTS METHODS

3.1 Pullout tests - Set up and test apparatus

Fig. 2 illustrates the experimental setup. The specimen was tested with the PVC pipe intact as a confining element. The PVC pipe was instrumented with a circumferential clip gauge in order to monitor the radial pressure induced during the pullout process. The clip gauge used to measure circumferential strains in the PVC pipe, and the LVDT, used to measure the slip at the free end of the anchor bolt are shown in Fig. 2b.

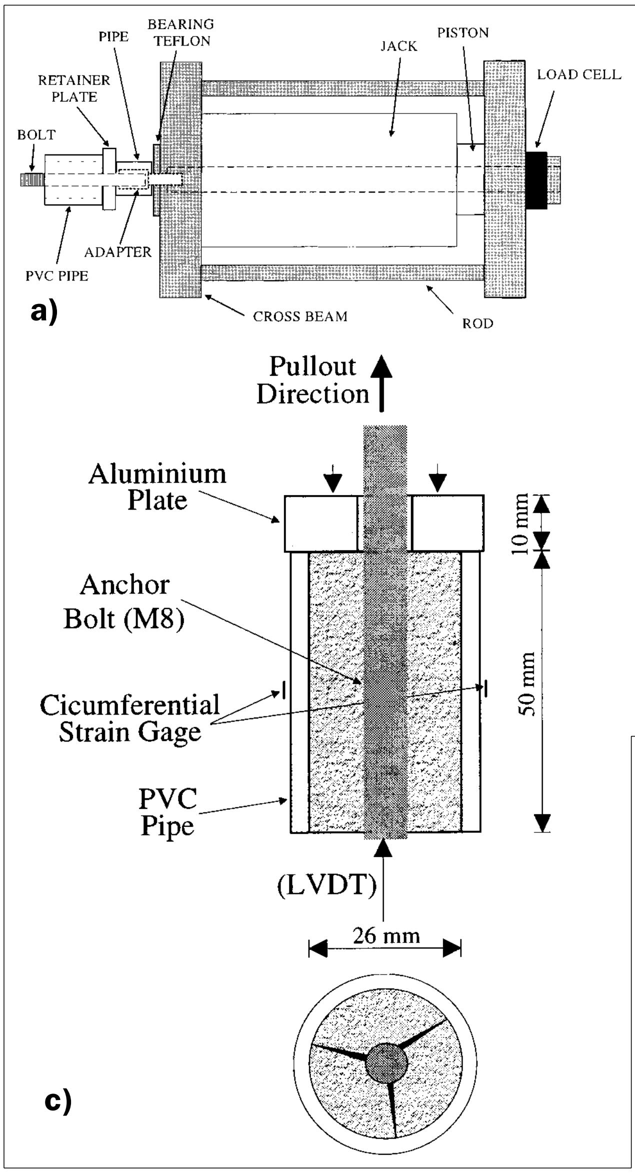
The threaded anchor bolt was pulled through a 10 mm hole in the bearing plate. The bolt was loaded with a 400 kN center bore hydraulic jack as shown in Fig. 2a, and the load was measured with a 25 kN load cell. Two aluminum rods were loaded in parallel with the specimen in order to avoid any brittle post-peak behavior.

The pullout load vs. slip of the bolt, as well as the circumferential strain in the PVC pipe were recorded. The shear stress (τ) was calculated based on the measured pullout load, assuming uniform shear stress along the bolt. The measured circumferential strain in the pipe was converted to radial stress in the cracked matrix, assuming hydrostatic pressure [8]. The radial stress (Fig. 2d) induced by the bolt pullout can be than computed:

$$\sigma = 2\varepsilon_p E_p t / d$$

when: σ = radial stress, ε_p = measured circumferential strain in the pipe, E_p = modulus elasticity of the PVC pipe (2760 MPa), t = thickness of the PVC pipe (3.4 mm), d = diameter of the bolt (7.8 mm).

For each composition at least 5 pullout specimens were tested.



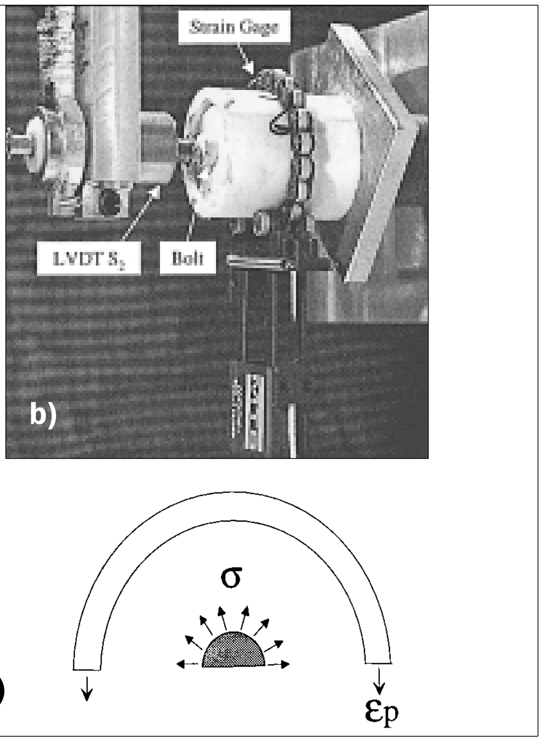


Fig. 2 – Experimental set-up, a) loading configuration, b) specimen set-up, c) longitudinal and transverse cross-sections of specimen, d) radial stress computed from measured PVC circumferential strain.

3.2 Compression tests

Compression tests were performed on a 138 KN MTS machine, using stroke control with a rate of 0.0025 mm/sec. The compressive load and axial displacement was recorded and the modulus of elasticity and compressive strength were calculated.

For each of the two compositions at least 3 compression specimens were tested.

3.3 Microstructural observations

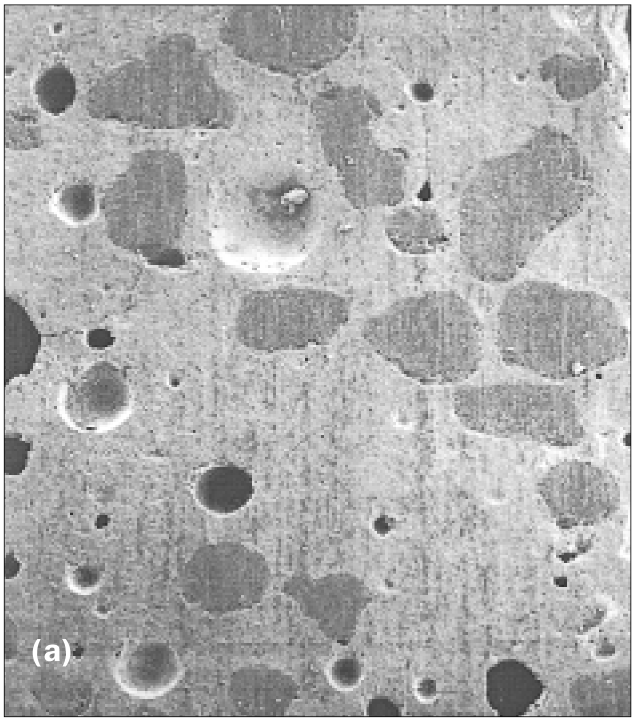
Scanning Electron Microscope (SEM) imaging was used to study the microstructure of the matrix and the bolt-mortar interface. The observations of the mortar-bolt interface along the bolt axis before and after the bolt pulled out were made. These observations focused primarily on the mortar groove around the threaded anchor bolts, looking specifically at locations near the unloaded and the loaded ends. In order to expose the groove of the matrix around the bolt without damaging the matrix groove, the specimens were notched along the longitudinal axis of the specimen and then split. SEM observations were also made on polished section cut transvere to the bolt prior to pullout. This was to examine the mortar microstructure and the distance between the bolt and the mortar at the mortar-bolt interface. All specimens were dried at 105°C and gold-coated prior to the SEM imaging.

3.4 Expansion measurements for wollastonite mortar

A significant expansion behavior of the wollastonite mortar during setting was observed, contrary to the shrinkage behavior of Portland cement. These volumetric changes during setting of Portland cement and wollastonite can effect the mortar-bolt bond and the pullout behavior of these systems. The average shrinkage of Portland cement mortar is reported to be between 700-2000 strain $x10^{-6}$. A rough estimate of the expansion behavior of the wollastonite mortar was obtained as follows. Two wollastonite mortars with 110 and 374 μm aggregate sizes were prepared. These mortars were pored inside PVC molds (as mentioned above) up to half of the

Table 3 – Effect of sand size on compressive strength, modulus of elasticity and expansion

	Portland cement		Wollastonite	
Average sand size	110 μm	374 μm	110 μm	374 μm
E (MPa)	13131	14161	8208	7019
f'c (MPa)	57	52	40	37
Expansion %	—	—	5 - 6	



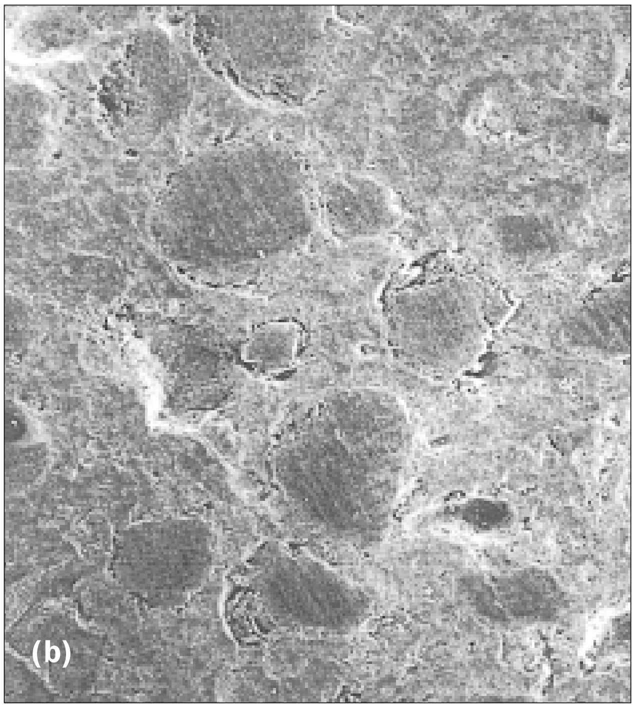


Fig. 3 – Microstrucure of the two mortar systems (40x): (a) Wollastonite (b) Portland cement.

mold length and let set. The length of the empty portion of the mold was measured before and after setting. Assuming that the volumetric changes of mortar inside the mold is reflected only in axial direction, the percentage of the difference in the length was calculated to determine the wollastonite expansion.

4. RESULTS AND DISCUSSION

4.1 Matrix properties

Table 3 presents the compressive performance of the mortars for both Portland cement and wollastonite, as well as the expansion properties of wollastonite, containing average sand grain sizes of 110 and 374 μm. The compressive strength and the modulus of elasticity were higher for Portland cement. This can be partly due to the higher porosity of Wollastoinite mortar compared to the low porosity of Portland cement mortar as shown in Fig. 3.

Fig. 4 shows SEM micrographs of bolt-mortar interface cross section for wollastonite and Portland cement mortars. A significantly smaller gap between the bolt and the wollastonite matrix can be seen compared to much larger gap in the case of Portland cement system. This can be related to the expansive behavior of the wollastonite system (Table 3). Note that these observations were taken when a good penetration of the wollastonite mortar inside the bolt threads was observed.

4.2 Mechanical behavior

Figs. 5, 6a and 6b compare the influence of sand grain size on the average pullout shear strengths and pullout behavior of the two mortar systems.

It can be seen that the pullout shear strength is higher in the case of Portland cement mortar compared to wollastonite mortar (Fig. 5). The denser matrix in the case of Portland cement (Fig. 3b) compared to the high porosity mortar in the wollastonite cement (Fig. 3a) can explain some of the higher pullout resistance of the Portland cement system.

The data also shows that in the case of Portland cement, the pullout strength increases with increasing grain size. The influence of grain size is noticeable for wollastonite specimens.

Figs. 6c and 6d show the development of radial, confining stresses (based on the measured circumferential strain mentioned earlier) at the bolt matrix interface. For both Portland Cement and wollastonite systems, the

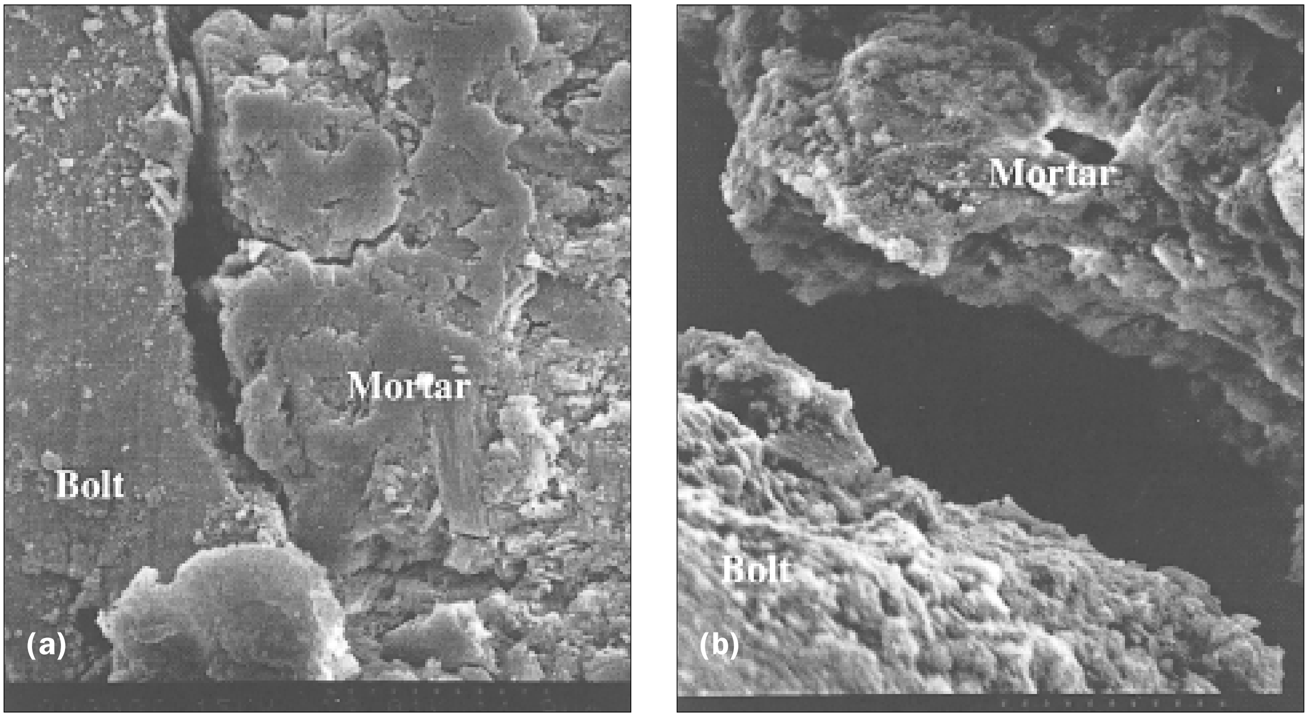


Fig. 4 – Bolt-mortar interface prior to pullout test x2000 (sand size 374 µm): (a) Wollastonite system, (b) Portland cement system.

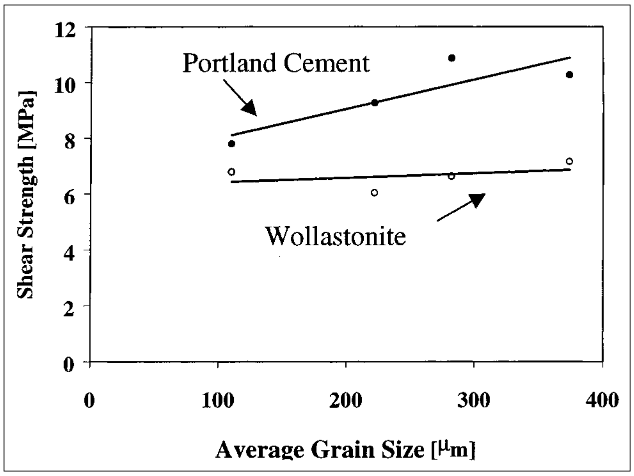


Fig. 5 – Effect of sand grain size on pull-out strength.

radial stress developed at peak shear stress (Figs. 6a and 6b) accompanied with radial cracking in the matrix. The magnitude radial stresses and the slips are influenced by the aggregate size and the mortar system:

(a) Effect of aggregate size - Increasing the sand grain size increases the radial stress in both systems. In the case of Portland cement the development of the radial stress begin to occur at a larger slip value for fine aggregate size compared to coarse aggregate size (Figs. 6c and 6d). In the case of wollastonite, no significant difference in that slip values at the initial of radial stresses was observed.

(b) Effect of mortar system - The maximum value of radial stress is larger in the case of wollastonite as compared to Portland cement. The build up of the radial stress occur at larger slip value in the case of Portland cement system compared to wollastonite system (Figs. 6c and 6d). These differences in radial stress and slip value mortar systems can be explained on the basis of the expansion behavior of wollastonite. As mentioned above the expansion of wollastonite mortar during setting leads to a denser bolt-mortar interface. The small gap between the matrix and the bolt in wollastonite cement system prior to the pullout test (Fig. 4a) requires only small slip value in order to develop the radial stress in the matrix (Fig. 6d). This dense bolt-mortar interface also leads to high circumferential strains in the mold during pullout, *i.e.* high radial stress for the wollastonite system (Fig. 6d). For Portland cement the large gap between the bolt and the matrix (Fig. 4b) requires larger slip to develop normal stress (Fig. 6c).

Fig. 7 shows the threaded bolts after pullout from Portland cement containing sand grain sizes of 110 µm and 374 µm. It can clearly be seen that the mortar penetrated inside the bolt threads and remained that way through the pullout process. The remaining mortar layer around the bolt is thicker in the case of the fine aggregate as compared to that observed for the coarse aggregate. This suggests a more aggressive pullout process in the case of coarse aggregate, as bigger part of the mortar abraded during the pullout process. The same tendency was also observed with the wollastonite mortar.

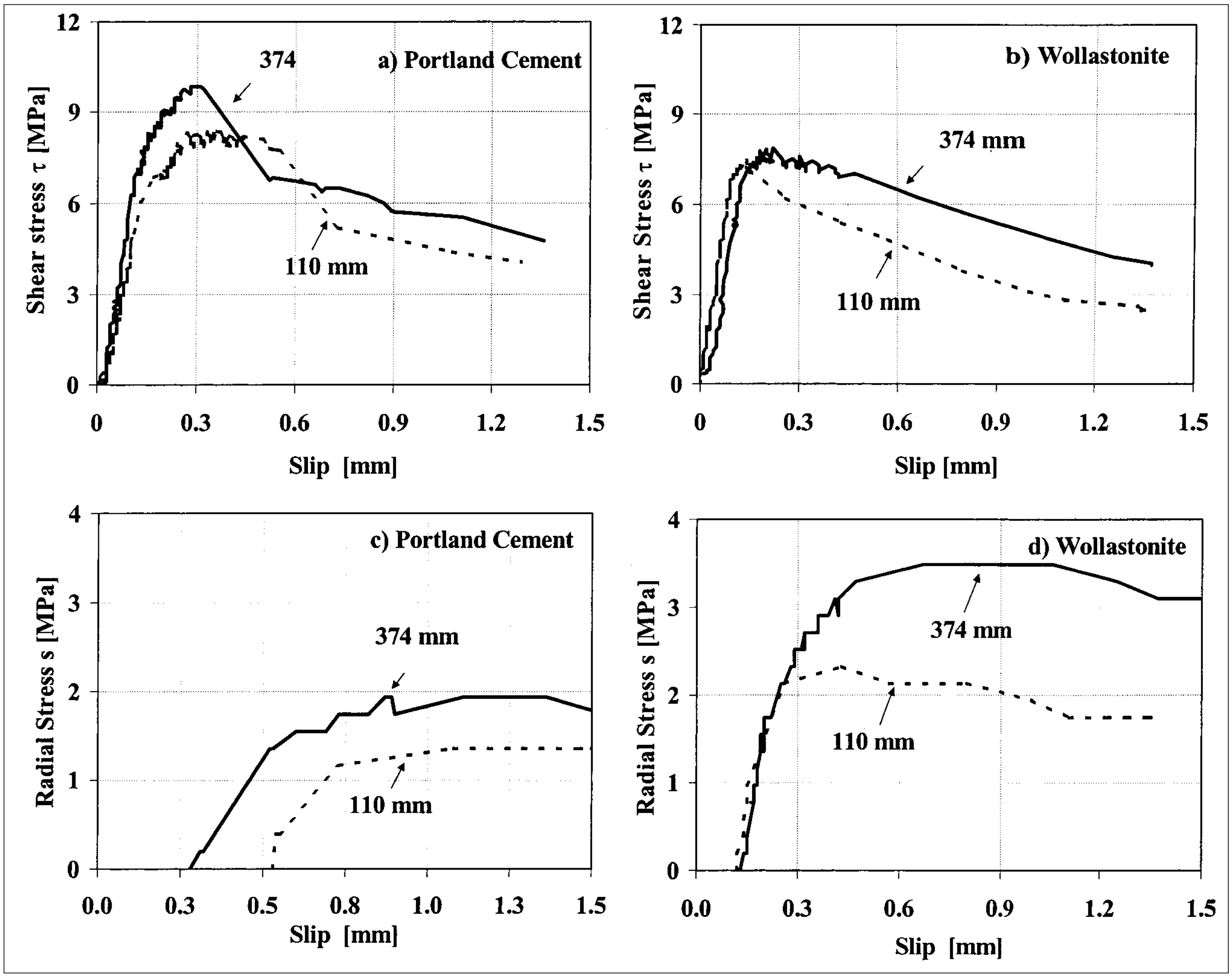


Fig. 6 – Shear and radial stress during bolt pull-out for portland cement and wollastonite systems: a) & b) shear stress vs. slip, c) & d) radial stress vs. slip.

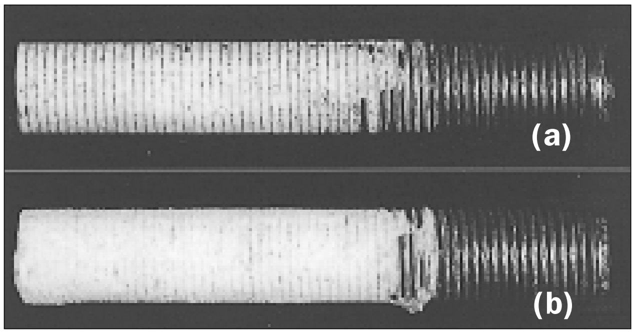


Fig. 7 – The threaded bolts after the pulling out from portland cement mortar: (a) coarse aggregate (374 μm), (b) fine aggregate (110 μm).

4.3 Microstructure

Fig. 8 shows that the coarse aggregates accumulate in front of the bolt thread tips at the bolt/matrix shear zone. This could be due to the fact that the relatively large size of the particles (~0.4 mm) compared to the bolt thread spacing (~1 mm), does not enable full penetration of the coarse aggregate in between the threads. This results in a rough surface at the bolt-mortar shear zone leading to a higher pullout resistance (Fig. 5). The mechanism involved is interlock of the coarse aggregate with the bolt threads, is idealized in Fig. 9. Fig. 9a shows a coarse sand particle at the shear zone, halfway in between the bolt thread, prior to the pullout process. During the pullout process this aggregate can be either, crushed, pushed inside the matrix or moved apart from the matrix, depending on the matrix strength and the aggregate-matrix bond. In the case of Portland cement mortar, crushed aggregates were observed at the bolt-matrix interface after pullout (Fig. 10b). This suggests high matrix strength and matrix-aggregate bond, which led to the high pullout resistance (Fig. 5). A weak aggregate-matrix bond was developed in the case of wollastonite mortar, since mainly uncrushed aggregates partly held by the wollastonite matrix were observed (Fig. 10a). This explains the low pullout resistance in that system. The above observations were at the bolt-matrix interface after the pullout process, at the

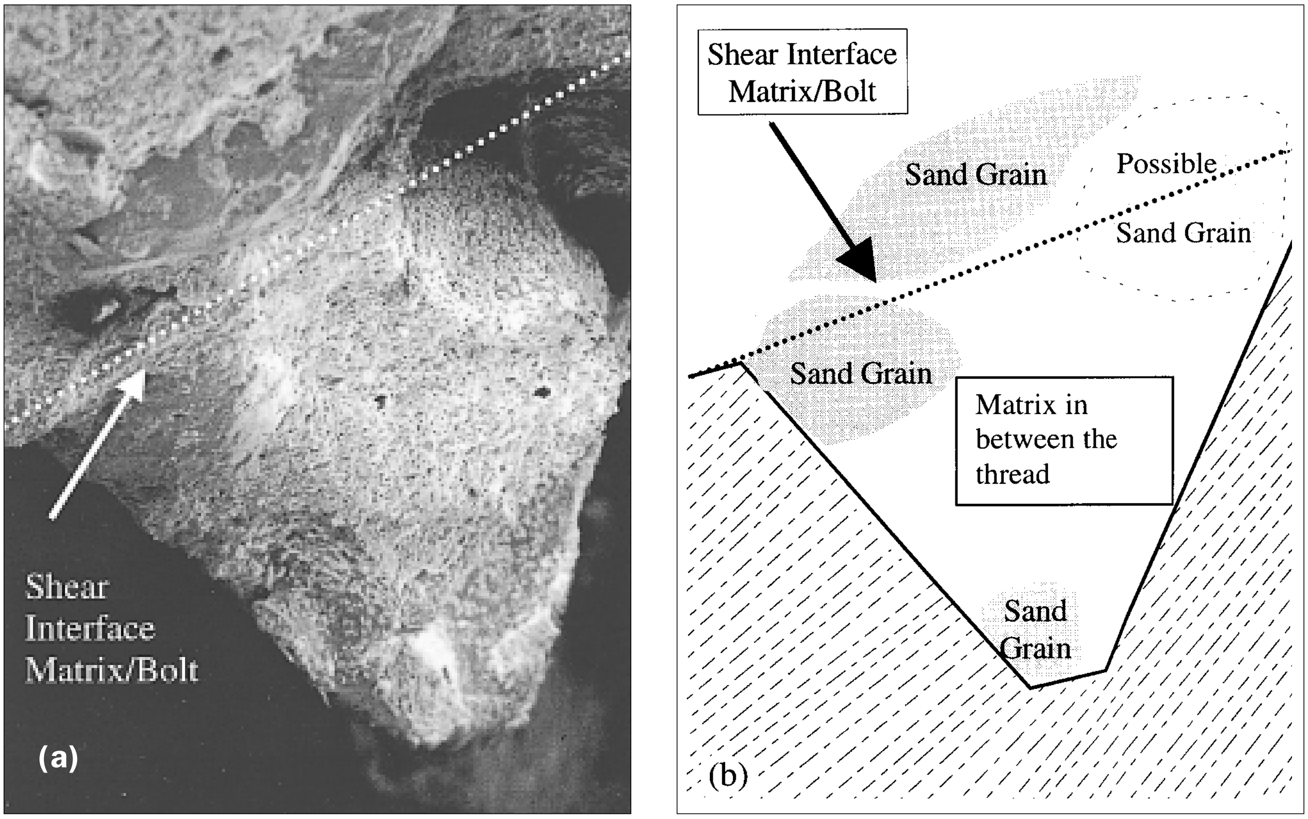
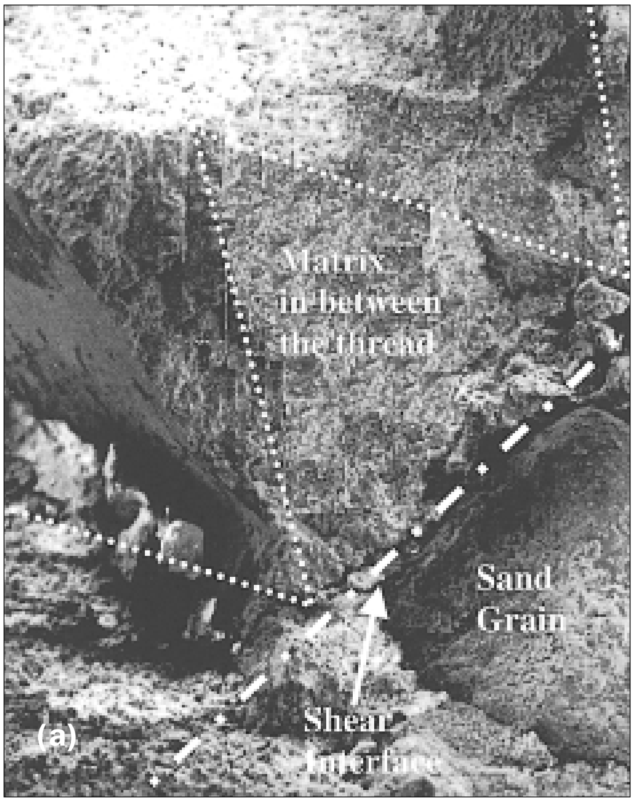


Fig. 8 – Dispersion of coarse aggregate in between and at the area of the threads: (a) SEM micrograph (100x), (b) sketch of the SEM picture.



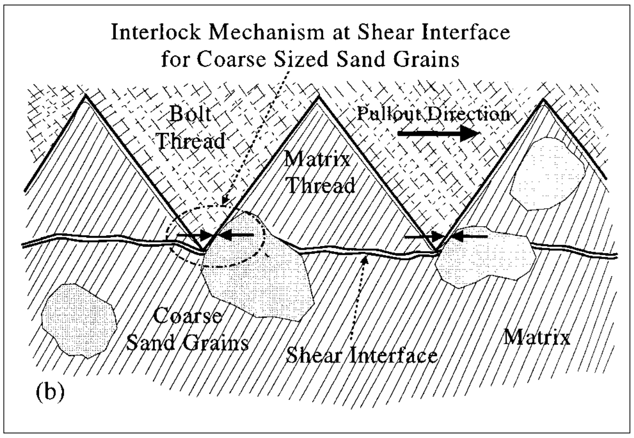


Fig. 9 – Coarse aggregate at the matrix-bolt shear interface: (a) SEM micrograph of coarse aggregate half way in the between the thread (70x), (b) sketch of interlock mechanism involved in this case.

loaded end of the specimen. Enhanced interlock mechanism caused by increasing the grain size can also be responsible for the increase in the radial stress with increasing the sand grain size (Figs. 6c and 6d).

For fine particle sizes, the size of the sand grains and a better dispersion of the sand grains in between the bolt threads (Fig. 11), lead to a less significant interlock mechanism. This results in lower pullout resistance compared to coarse aggregate (Fig. 5). This can also lead to larger slip value needed to develop radial stress in the mortar in the case of fine aggregate system compared to lower slip value for coarse aggregate system (Fig. 6). These are mostly true with Portland cement, since in wollastonite the interlock mechanism is less effective due to

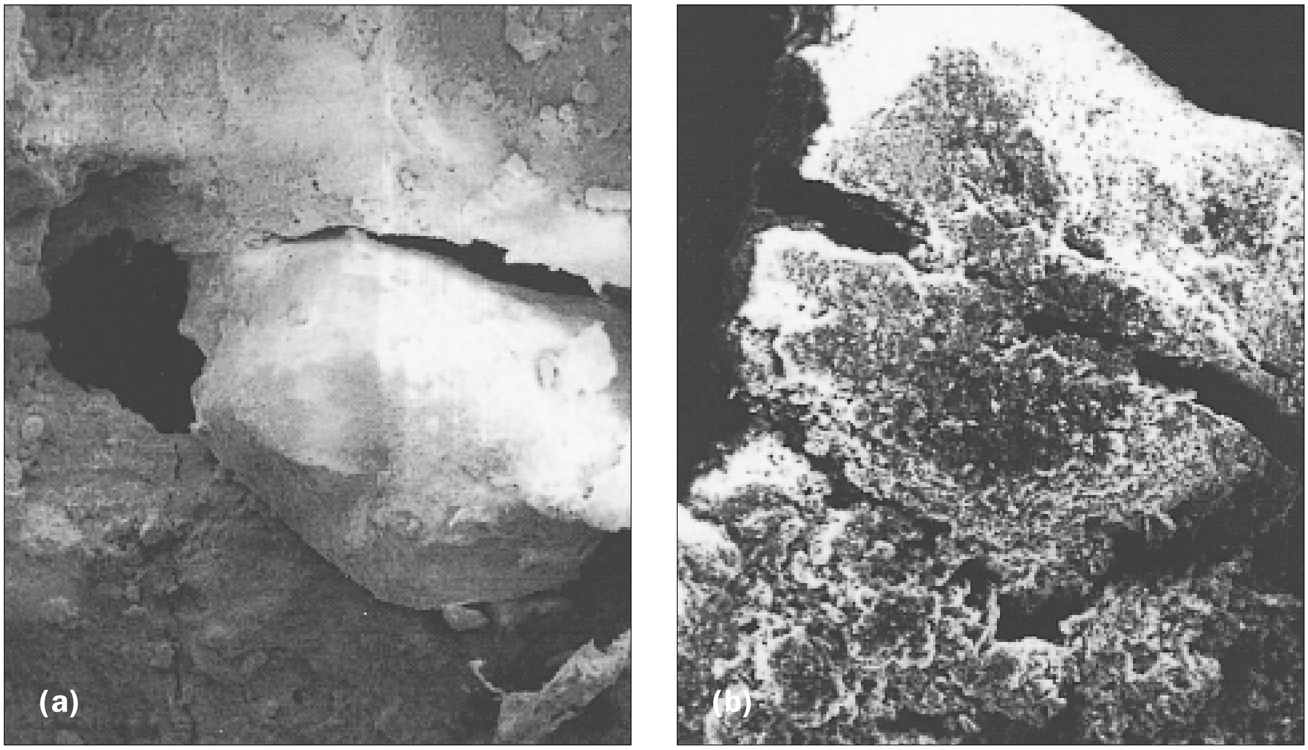


Fig. 10 – Coarse aggregate at the bolt-matrix interface after the pullout process, near the loaded end of the specimen: (a) uncrashed aggregate in Wollastonite mortar (110x), (b) crushed aggregate in Portland cement mortar (400x).

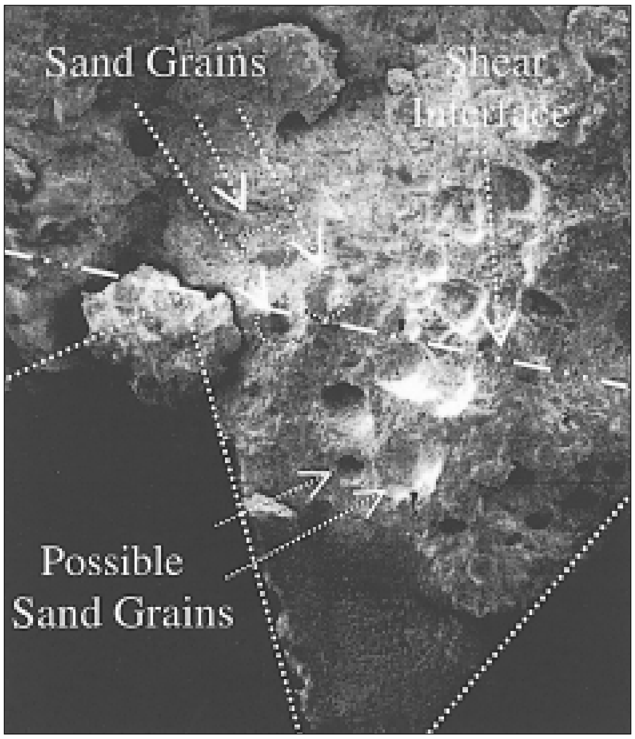


Fig. 11 – Dispersion of fine aggregates in between the bolt threads (70x).

the poor wollastonite cement strength and poor cement - aggregate bond.

A poor penetration of the wollastonite mortar in between the bolt threads can be seen in Fig. 12a, which also result in the low pullout resistance of the wollastonite mortar. Compacted mortar in between the bolt threads was observed in the case of Portland cement mortar, (Fig. 12b), which may have contributed to the higher pullout resistance. Fig. 12 was taken prior to the pullout process.

5. CONCLUSIONS

1. The pullout shear strength is higher in the case of Portland cement mortar compared to wollastonite mortar. This could be due to the low aggregate-matrix bond, the poor penetration of matrix in between the bolt threads and the low strength of the wollastonite matrix itself. This difference in the pullout resistance between the two mortar systems was more pronounced when coarse aggregate were used.

2. The pullout shear strength increases with increasing grain size in the case of Portland cement. The influence of grain size is less significant in the wollastonite mortar. These trends can be explained on the basis of the cement strength and aggregate-cement bond properties and the roughness of the matrix at the shear interface zone. For the Portland cement mortar system the aggregate-cement bond is higher compared to the wollastonite mortar system, which leads to a stronger interlock mechanism between the aggregate and the cement during the pullout process. For fine particle sizes, the size and a better dis-

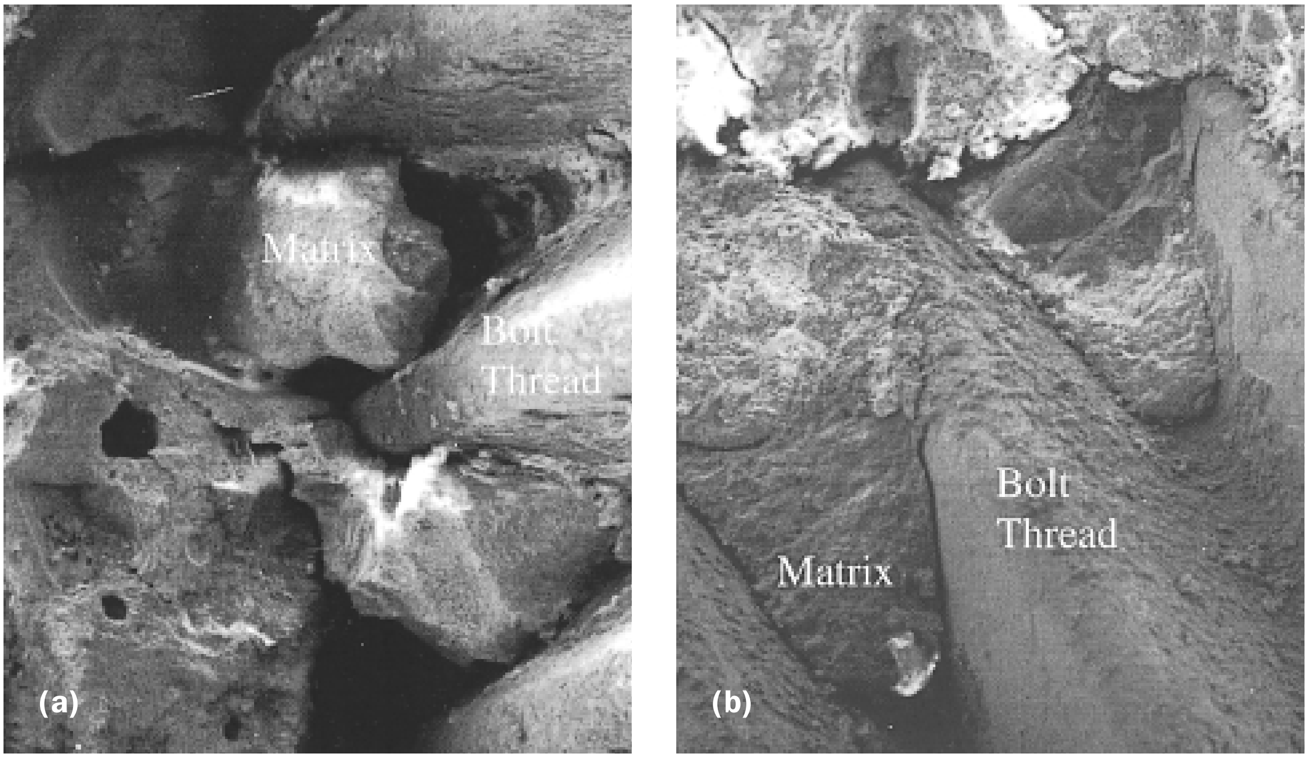


Fig. 12 – Penetration of the matrix in between the bolt threads (40x): (a) Wollastonite mortar, (b) Portland cement mortar.

persion of the sand grains in between the bolt threads, leads to a smoother fracture surface of the matrix at the interface. This creates a less significant interlock mechanism, which results in lower pullout resistance. This was mainly the case with Portland cement. In the wollastonite mortar the interlock mechanism is not very significant even with coarse aggregate, due to the poor cement strength and cement - aggregate bond. It was observed for wollastonite mortar that the aggregates were pushed inside the matrix or moved apart from the matrix by the bolt thread during the pullout process.

3. Radial stresses developed at reaching the peak shear stress accompanied with radial cracking in the matrix, for both Portland cement and wollastonite systems. The values of the normal stresses and the slip values required to develop radial stresses are affected by the aggregate size and the mortar system. These differences can be explained on the basis of the expansive behavior of wollastonite mortar during setting. The expansive behavior of wollastonite system led to a small mortar-bolt gap. Small slip was therefore required to develop high normal stress in the mortar. For Portland cement system larger slip value was required to develop lower normal stress in the mortar. This was due to a significantly larger gap at the bolt-mortar interface.

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