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THE MECHANICAL PROPERTIES OF POZZOLANIC LIME MORTARS USED AS FILLER MATERIAL IN THE RESTORATION OF ANCIENT MONUMENTS

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Abstract. *This paper focuses on the experimental investigation of the mechanical properties of a pozzolanic mortar. Mortar specimens were prepared by mixing aggregates (fine carbonate sand), binder (hydrated lime and metakaolin) and water. Two series of uniaxial compression tests and triaxial compression tests were performed in order to determine the uniaxial compressive strength and the triaxial compressive strength respectively. Cylindrical specimens were prepared by casting the mortar mix into a metal mold. Prior to testing the properties of the mortar specimens, a number of tests was performed in order to evaluate the design of the casting mold, the lubricant used within the casting mold, and the curing time of the mortar. The cylindrical specimens for the uniaxial and the triaxial compression tests measured 50 mm in diameter and 100 mm in height. Testing rates followed the ISRM suggested methods and the axial load was applied using a stiff 1600 kN MTS hydraulic testing machine and a 500 kN load cell. Triaxial compression tests were carried out using a hydraulic confining chamber with a maximum pressure capacity of 14 MPa.*

1 INTRODUCTION

Mortars are the result of mixing sand grains, a binder (lime, cement, etc.) and water. The properties and characteristics of each type of mortar depend decisively on the nature of the binder component. This is why the evolution of mortar products is closely related to the development of artificial cementitious materials. In a brief historical overview, it is worth noting that during the dominance of the Roman Empire the use of lime mortars was generalized and extended. Since the XVIIIth century, hydraulic binders begun to partially replace lime. These new materials hardened more quickly and developed higher mechanical strengths. In the XIXth century, the invention of Portland cement revolutionized the world of building materials, completely displacing the use of lime in all types of civil and military constructions [1].

The design of mortars with binders of hydraulic lime and/or hydrated lime and metakaolin has been investigated in the literature [2,3,4,5] in order to examine its physico-chemical and mechanical parameters. Nowadays, hydrated lime–metakaolin mortars are increasingly preferred in the restoration and conservation of architectural monuments, due to their enhanced chemical, physical, structural and mechanical compatibility with historical building materials (stones, bricks and mortars) [6].

The mechanical properties of mortars that are typically used in strength calculations, such as the compressive strength, tensile strength and elastics properties have been reported in the literature. This paper, presents experimental results developed as a result of triaxial loading of mortar specimens consisted of hydrated lime and metakaolin. In addition, it discusses the procedure used to achieve an acceptable design of the casting mold and the lubricant used prior to casting.

2 TESTING MATERIALS AND METHODS

2.1. Composition of the pozzolanic mortar

The mortar used in the experiments described below consisted of carbonate sand, binder of hydrated lime (CaO Hellas) with metakaolin (Metastar 501 by Imerys), and deionized water.

Taking into account that fine aggregates can contribute to the avoidance of shrinkage and cracking during the setting process, it was deemed important to add sand of carbonate nature with fine grains in the mix design. Therefore, aiming at improving the bond strength between mortar and porous stone, equal proportions of carbonate sand passing through the 125 and 63 μm sieves, were subjected to thorough water washing to free the harmful soluble salts before adding to the mix.

Metakaolin is a highly active aluminosilicate material, which is formed by the dehydroxylation of kaolin $Al_2(OH)_4Si_2O_5$ that occurs by thermal treatment in the 650–800°C temperature range. The raw products were characterized by XRD, FTIR, DTA-TG and EDXRF techniques. Metakaolin presents a fine grain size distribution (cumulative passing from 24 μm: 100% and from 16 μm: 95.6%) as estimated by laser particle size analyzer (Mastersizer 2000 particle analyzer, Malvern). X-ray diffraction analysis revealed that metakaolin is amorphous with minor content of mica, quartz and feldspar. As far as the pozzolanic activity of MK is concerned, the percentages of total silica and active silica (according to EN 197-1 and EN 196-2) were determined as 54.2% and 44.6%, respectively [7]. The pozzolanicity of metakaolin, i.e. the uniaxial compressive strength of a mixture of hydrated lime and metakaolin and carbonate aggregates of a standard grain size distribution, according to Greek Presidential Decree 244/1980, article 8, reaches up to 13.1 MPa [5, 7].

Table 1 presents the mortar mix used in this series of experiments. The water to binder (W/B) ratio was 0.92 for all mixes. The mixing tools and materials were stored at a constant temperature of 23 °C for 24 h before mixing. The quantity of hydrated lime that would react with metakaolin was fixed in a weight ratio equal to 1.5, ensuring the pozzolanic reaction, while any unreacted quantity of hydrated lime, after its carbonation, provides elasticity to the final mortar. This excess of hydrated lime after its carbonation, enables the mortar to acquire a pore size distribution similar or compatible to porous stone, thus facilitating the homogeneous distribution of water and water vapor in the complex system [6,7].

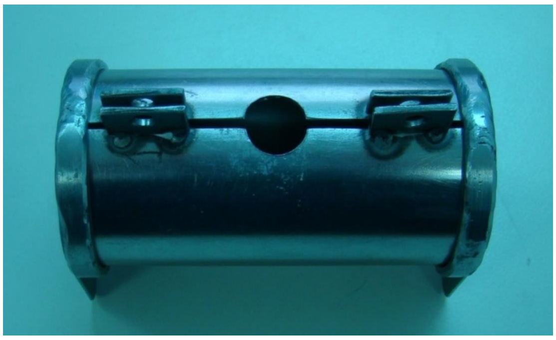
Sand	Binders		B/A	W/B
	Lime	Metakaolin		
50	30	20	1	0.92

Table 1. Mortar mix (composition in mass %), B: binder, A: aggregates, W: water

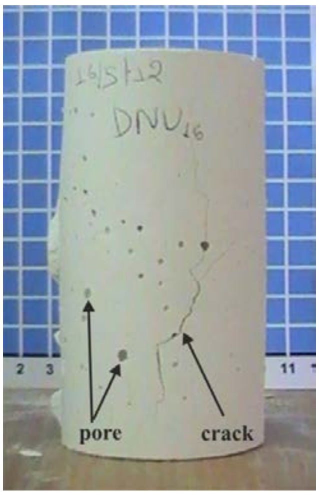
2.2. Mortar casting

The compressive strength of mortar is usually determined based on cubic specimens cast in respective molds. The cubic mold design allows the preparation of at least two opposite parallel and flat surfaces according to the necessary specification. To satisfy the requirements of triaxial testing, however, it was necessary to prepare cylindrical specimens, ensuring that the two bases of each cylinder would be parallel to each other and flat according to the relevant specifications. The dimensions of the cylindrical specimens were: diameter D = 50 mm and height h = 100 mm.

The mold that was initially designed and constructed is shown in Fig. 1a. The mold was lubricated with light machine oil and casting was achieving through a small hole on the side of the cylinder. After casting, the filled mold was placed on a vibrating surface for one minute to ensure uniform placement of the material. However, this first attempt to prepare mortar specimens was unsuccessful. The main problems that were identified were two: a) mortar pieces broke off from the cylinder bases during mold disassembly and b) large voids (pores) due to air bubbles and small cracks were evident on the cylindrical surface of most specimens (Fig. 1b).



(a)

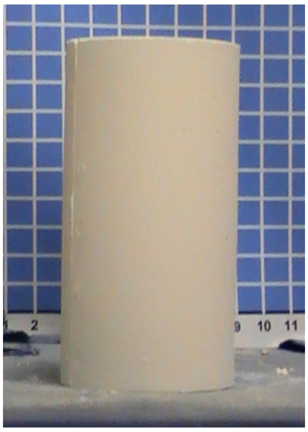


(b)

Figure 1. (a) The initial mold design (b) Specimen with large voids and cracks.

Following these initial attempts, a new mold was designed and constructed as shown in Figure 2a. This design allowed for a milder disassembly process that did not break the freshly molded specimens. Furthermore, the lubrication mix used on the mold was modified and replaced with a mixture of olive oil and liquid soap in water. Thus the number of large voids and initial cracks on the surface of the specimens was substantially diminished. After casting of the mortar, the mold was placed in a curing chamber for setting, at Relative Humidity (RH)=90-95% and Temperature (T)=20^{o}C, according to the procedure described in the EN 196-1 standard. Specimens were cured for about 26 days under the above conditions and then they were set to room conditions for two days prior to testing. A typical specimen obtained from the new casting process shown in Figure 2b.

(a)



(b)

Figure 2. (a) The improved mold (b) Specimen without pores and cracks.

3 EXPERIMENTAL SETUP

3.1 Equipment and test specifications

The mechanical properties of the mortars were characterized by measuring the uniaxial compressive strength (UCS) and the triaxial compressive strength (TCS) according to the ISRM specifications [8,9]. For these tests, the mortar was considered an isotropic material and, therefore, the orientation of the specimens was not taken into account. The cylindrical specimens were prepared according to the ISRM specifications [8,9] for the uniaxial compression and triaxial compression test respectively. The height *h* to diameter *D* ratio for these tests remained constant and equal to 2.

Axial load for the uniaxial compression tests was applied using a stiff 1600 kN MTS hydraulic testing machine and a 500 kN load cell. For the triaxial tests, a Wykeham Farrance triaxial testing apparatus with a maximum lateral pressure capacity of 14MPa was employed. Axial load was applied again using the 1600 kN MTS loading frame, but without the 500 kN load cell. The axial load was applied under displacement control mode for both uniaxial and triaxial compression tests. The displacement rate was set to 0.01 mm/s for both experiment groups.

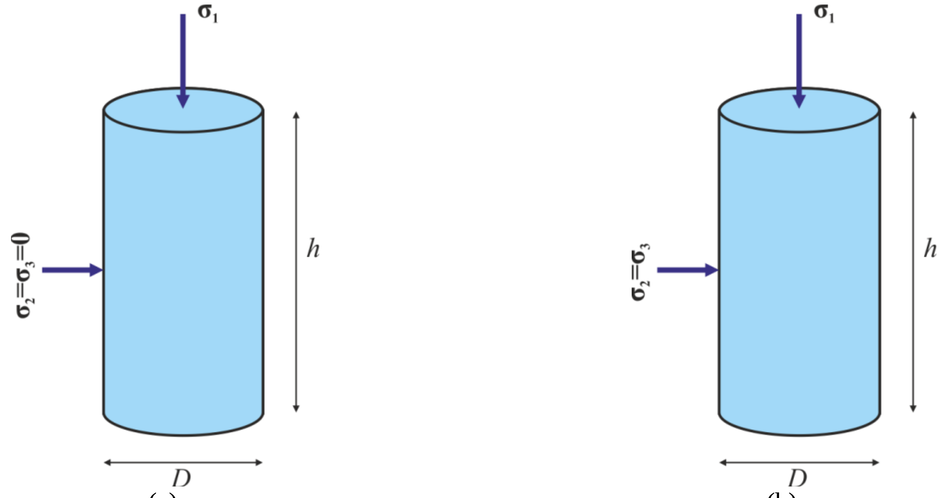
3.2 Uniaxial compression test

In uniaxial compression tests a cylindrical specimen of diameter *D* and height *h* is subjected to a uniformly applied load *P*, acting on the ends of the specimen (Fig. 3a), following the ISRM suggested method [8].

3.3 Triaxial compression test

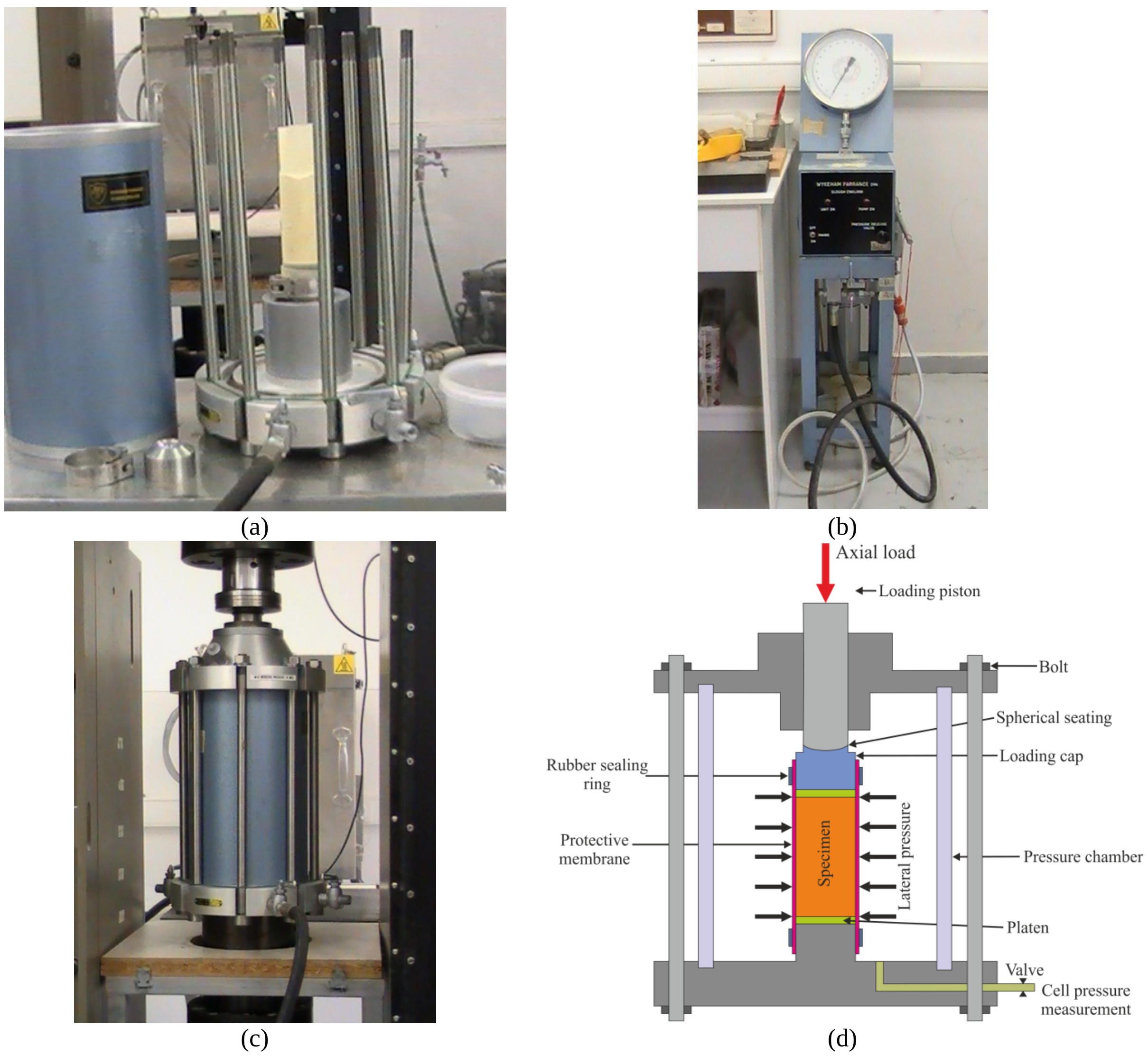
The triaxial compression test (Fig. 3b) is a laboratory test method that is used to assess the mechanical properties of materials that may be subjected to multiaxial loading. It provides a measure of the confined compressive strength under different confining pressures, as well as the stress-strain characteristics of the material specimen. It is commonly used to estimate the confined strength of rocks and soils by simulating the in situ confining (geostatic) pressures. Triaxial compression tests performed over a range of confining pressures are used to determine the strength envelop of a material as well as its strength and deformation and characteristics.

Each specimen is enclosed in a thin rubber membrane and placed inside a pressure vessel (Fig. 4a). The pressure vessel allows the specimen to be loaded hydrostatically to the desired confining pressure while the rubber membrane prevents the confining fluid from entering the specimen pore space. In a conventional triaxial compression test the specimen is first loaded hydrostatically to the desired confining pressure with the aid of the lateral pressure controller (Fig. 4b) and then the axial load is increased until specimen failure occurs, while holding the confining pressure constant.



(a) (b)

Figure 3. (a) Uniaxial compression test. (b) Triaxial compression test.



(a) (b) (c) (d)

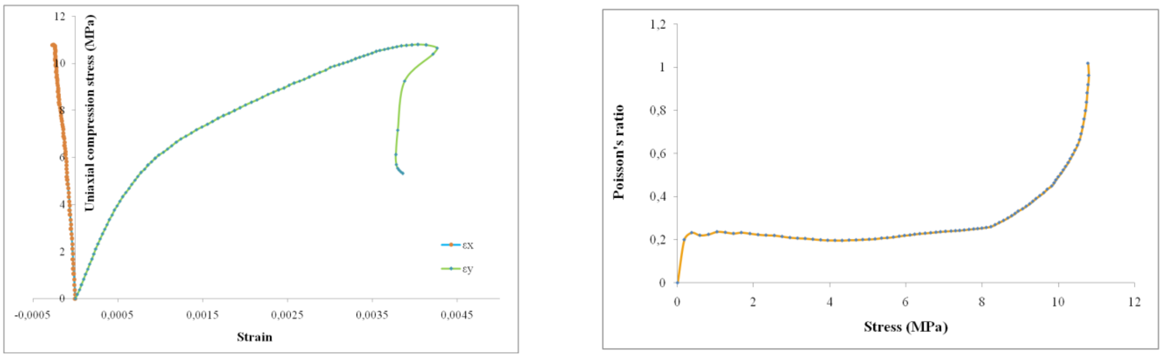
Figure 4. (a) Lateral pressure controller (b) Specimen with the rubber membrane (c) Triaxial cell in MTS testing machine (d) Setup of the triaxial compression test.

The applied load and resulting deformation are measured with the data acquisition system to generate load-deformation curves. The pressure vessel was inserted in the loading frame of the MTS stiff testing machine (Figure 4c) and the load application sequence was manually coordinated between the two units. A schematic diagram depicting specimen setup inside a triaxial cell is shown in Figure 4d. For these tests, axial deformations were measured external to the pressure vessel, while lateral specimen deformations were not measured.

4 EXPERIMENTAL RESULTS

4.1 Uniaxial and triaxial compression test results

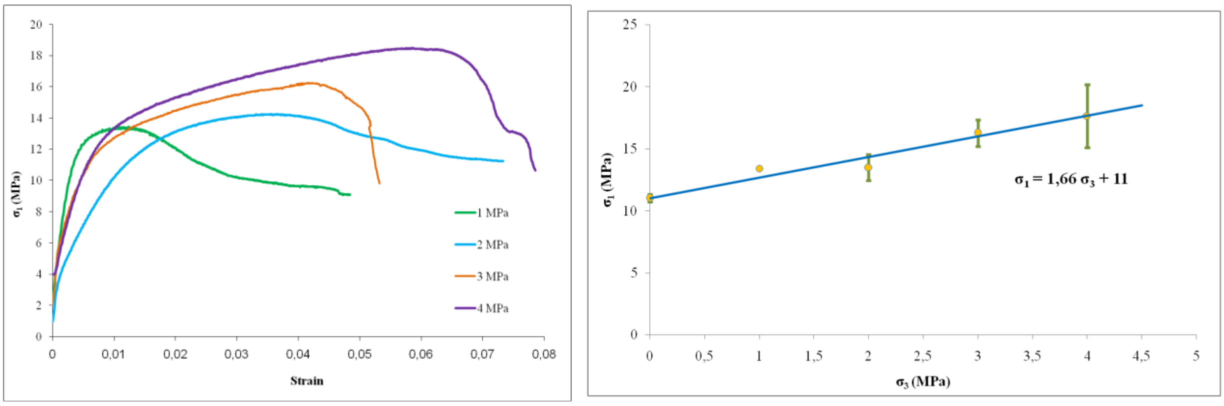
In the present work a total of two (2) uniaxial compression and 11 triaxial compression tests were completed, in order to investigate the mechanical properties of the pozzolanic mortar. It should be noted that the specimens used for these tests where only those that were cast using the second edition of the mold and the updated lubrication methodology. Indicative uniaxial compression test results are presented in Fig. 5a and Fig. 5b.



(a) (b)

Figure 5. (a) Axial stress vs axial and lateral strain (b) Variation of Poisson's ratio with the axial stress.

Four different sets of the triaxial compression tests were conducted, by applying a different lateral pressure σ_3 = 1, 2, 3 and 4 MPa for each set. Figure 6a presents indicative axial stress – strain curves for each lateral stress value, while the mean values of the confined uniaxial strength σ_1 vs the lateral stress σ_3 are shown in Figure 6b. A linear trend line was applied to the average σ_1, σ_3 values for each lateral pressure level. This linear trend represents a linear Mohr-Coulomb strength criterion [10] in σ_1, σ_3 axes.



(a) (b)

Figure 6. (a) Stress – strain curves for different lateral stresses (b) Confined uniaxial compression strength vs lateral stresses.

4.2 Mode of fracture

Almost all of the pozzolanic mortar specimens subjected to uniaxial compression tests failed along a single shear plane (Fig. 7a). The same failure mode was also observed for the specimens subjected to triaxial compression (Fig. 7b). Some specimens, such as D25 (Fig 7b), exhibited a pronounced lateral expansion in addition to the shear plane that was responsible for their failure.

(a) (b)

Figure 7.Typical crack patterns in pozzolanic mortar cylindrical specimens in (a) uniaxial compression test and (b) triaxial compression test.

5 DISCUSSION AND CONCLUSIONS

This paper presented the experimental procedure and results for determining the uniaxial and triaxial compression parameters of pozzolanic mortar specimens. Cylindrical specimens with a 2:1 height to diameter ratio where employed instead of the usual cubic specimens. This allowed the direct comparison of uniaxial and triaxial test results. To date there the published international literature does not include triaxial compression experimental results for mortars performed on cylindrical specimens.

As expected, the confined uniaxial strength σ_1 increases as the lateral stress σ_3 increases. Furthermore, the stress-strain curves for σ_3=2, 3 and 4 MPa in Fig. 6a and the lateral expansion of specimen D25 in Fig. 6b confirms that many specimens in triaxial compression test exhibits plasticity.

Using the experimental results shown in Fig. 6b, a single Mohr's Circle was plotted using the mean σ_1, σ_3 values for each lateral pressure level (Fig. 8). Subsequently, a line tangential to at least two circles was draw which represents the so called the Mohr-Coulomb failure envelope [11] and is given by equation (1).

$$\tau = 5 + 0.1824 \cdot \sigma \tag{1}$$

The trend line shown in Fig, 6b which is given by equation (2) was then transformed in $\tau - \sigma$ space using equations (3) (where C_o is the uniaxial compression strength, S_o is the cohesion and ϕ is the angle of internal friction) and is given by equation (4).

$$\sigma_1 = 11 + 1.66 \cdot \sigma_3 \tag{2}$$

$$\sigma_1 = C_o + q \cdot \sigma_3 \qquad C_o = S_o \frac{2\cos\phi}{1+\sin\phi} \qquad q = \frac{1+\sin\phi}{1-\sin\phi} \tag{3}$$

$$\tau = 4.27 + 0.2562 \cdot \sigma = 4.27 + \tan(14.37^o) \cdot \sigma \tag{4}$$

It is expected that equations (1) and (4) are different (also depicted in Fig. 8) because the first represents a linear envelop failure line, while the second represents a least square approximation of the mean values of the σ_1, σ_3 pairs that were determined experimentally.

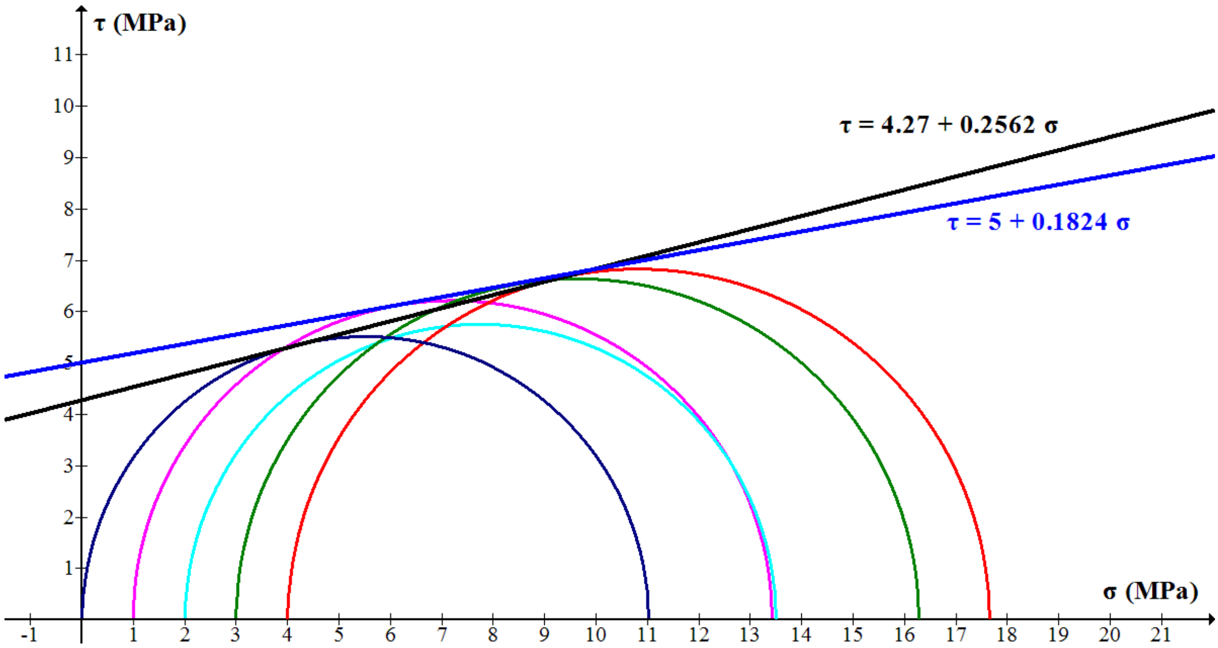


Figure 8. Mohr-Coulomb failure envelope.

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