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Experimental study of the mechanical behavior of plastic concrete in triaxial compression

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Abstract

This paper is going to present the results of an extensive experimental parametric study of the mechanical responses of various types of plastic concrete in unconfined and triaxial compression tests. Plastic concrete consists of aggregates, cement, water and bentonite, mixed at a high water cement ratio, to produce a ductile material. It is used for creating an impermeable barrier (cut-off wall) for containment of contaminated sites or seepage control in highly permeable dam foundations. A plastic concrete cut-off wall acts essentially as a barrier to stop or reduce the groundwater flow. In this study the effect of specimen age, cement factor, bentonite content and confining pressure on shear strength and permeability of plastic concrete were investigated. The observed behavior is more and more ductile for increasing confining pressure. It is shown, also, that any increase in confining pressure increases the compressive strength as well as the elastic modulus and the deformability of the specimen. It is shown that an increase in cement factor increases the shear strength as well as the elastic modulus. It is obtained that increase of bentonite content, decreases the compressive strength as well as the elastic modulus. Increasing the age of the specimens causes an increase of the compressive strength as well as the elastic modulus and also the shear strength parameters are affected. Also, it is obtained that increase in confining pressure and cement factor reduces the permeability.

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Keywords: Mixture proportioning; Compressive strength; Elastic moduli; Permeability; Plastic concrete

1. Introduction

Slurry walls, constructed by normal or plastic concrete, are today among the most classic geotechnical technologies and have been widely used both for structural purposes (structural walls) and for hydrogeological purposes (cut-off walls). The latter, aimed to prevent and/or modify the groundwater flow, have been extensively used in many different fields of civil engineering, such as dams, reservoirs, tunnels, dewatering projects, and so on. Concrete cut-off walls are also used for the purpose of confining underground-contaminated sites. In dam engineering, this technology is used for the construction of the slurry cut-off wall in highly permeable dam foundations.

Seepage control is critical to the safe operation of earth dams. While remedial seepage control can be achieved with a rigid concrete cut-off wall, deformation of the earth embankment and its foundation can cause the concrete wall to rupture. Therefore, materials selected for construction of cut-off walls must be strong and watertight and have stiffness comparable to the surrounding soil. Satisfying strain-compatibility between the wall and surrounding soil will lessen the likelihood of overstressing the wall and will allow the wall and soil to deform without separating. Plastic concrete consists of the same materials as those of normal concrete with a high water–cement ratio and the only difference is that bentonite is added to the mixture to increase its ductility. This kind of concrete shows great promise for satisfying the strength, stiffness and permeability requirements for remedial cut-off wall construction [1–4].

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It is recommended that the modulus of the filling materials of the diaphragm wall and the adjacent soil should be in the same order to have the deformation compatibility and to prevent from the stability problems. As a guideline, ICOLD [3] proposes that the elastic modulus of plastic concrete should be one to five times of the elastic modulus of surrounding soil.

Because of the considerable load (dam body weight) on dam foundation and cut-off wall, the mechanical properties and behavior of the filling material of the diaphragm wall is also very important. Because of the confining effect of soil on cut-off wall (triaxial condition), careful study of the effect of triaxial stress condition on mechanical behavior of plastic concrete is important and necessary for the numerical approaches of the analysis of the cut-off wall under a dam body.

Although most researches have been carried out on the mechanical behavior of plastic concrete in unconfined compression tests [1,3,4], the results of triaxial tests are rare and the existent results are not completely appropriate for practical purposes, so the mechanical behavior in triaxial stress condition needs to be carefully investigated.

Regarding the results of the unconfined and triaxial compression tests, the effect of cement factor, bentonite content and water–cement ratio on the mechanical behavior of plastic concrete and its permeability have been studied. Experimental results were used to quantify the relative influences induced by the various parameters and the effectiveness of each parameter on the mechanical behavior change.

2. Experimental details

2.1. Materials and specimens

In this study, eight different plastic concrete mixes have been chosen for studying the various effective factors on plastic concrete properties as cement factor, bentonite content and water–cement ratio. Plastic concrete mixes, whose material proportions are shown in Table 1, were used to make the specimens for the different triaxial and unconfined compression tests. Specimens were cast in φ10×20 cm cylindrical molds and cured in saturated condition. Sufficient specimens were prepared for the programmed tests. Triplicate specimens of the standard size (cast in cylindrical molds φ15×30 cm) were prepared for the simple compression test.

Grain-size distribution curves of the aggregates (sand and gravel) are shown in Fig. 1. Sulphate resistant cement (type V) is used in all mixes. Because of its very low permeability, bentonite is mixed with water by a high-speed mixer 24 h before introducing to cement and aggregates to assure a homogenous distribution of bentonite particles in mixture and to obtain a homogenous mix.

2.2. Test procedure

The apparatus used in this study is a typical displacement-controlled triaxial cell. For performing the triaxial tests on prepared specimens, a new triaxial cell (Fig. 2) was designed and fabricated which equipped with steel walls in order to sustain the relatively high confinement pressure up to 3 MPa.

Tests were done in strain control mode, with constant confining pressure during the test. The cell is fully computer controlled in data acquisition. The axial displacement is imposed by means of a controlled speed driven motor, with the compression force up to 100 kN and an axial movement control of 0.0001 mm/min, and this motor allows speed-controlled tests to be performed. Cell pressure is generated by pressurized water and a high-pressure constant rate pump was used to produce it. Tests were done with the confining pressures of 0, 100, 300, 500 and 800 kPa. The strain measurements are made by means of an external displacement transducer and a volume gauge transducer.

Regarding the mechanical behavior of plastic concrete, whose strain corresponding to peak of axial stress is 0.004–0.009, it can be compared with a brittle cemented soil. Therefore, according to the recommendations of ASTM-D2166 and ASTM-D2850 [5,6] about the unconfined and triaxial test on cohesive soils, axial strain rate of 0.005 min^{-1} has been selected. For a specimen of 20 cm of height, the corresponding speed of piston for this rate of specimen

Table 1
Mixing proportions and consistency of the fresh concrete mixes

Mix	Cement factor (kg/m^3)	Water–cement ratio, W/C	Bentonite content B/C	Slump (cm)	Sand (kg/m^3)	Gravel (kg/m^3)	
						5–9.5 (mm)	9.5–19 (mm)
R19	220	1.59	0.14	17.5	705	300	495
R139	220	1.59	0.16	17	705	300	495
R140M	220	1.59	0.17	19	705	300	495
4Z	220	1.82	0.18	22	705	300	495
R140MD	200	1.75	0.20	18	705	300	495
R140MB	210	1.67	0.19	18	705	300	495
QC-5	200	1.75	0.19	18	705	300	490
R125	120	2.92	0.33	18	700	800	–

C: Cement, W: Water, B: Bentonite.

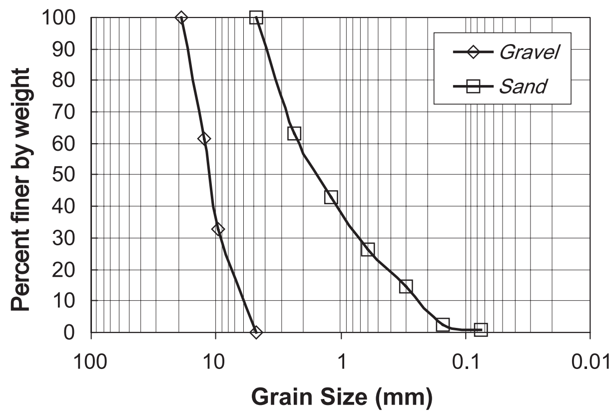

Fig. 1. Grain-size distribution curves of the aggregates.

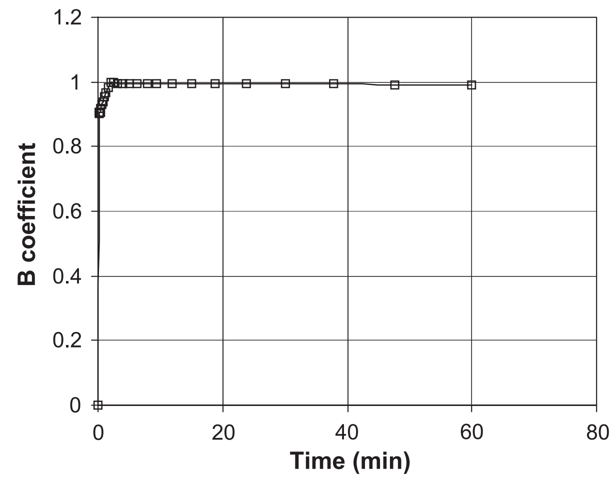

Fig. 3. Evolution of ***B*** coefficient during the specimen saturation.

loading is equal to 0.1 mm/min. This low strain rate is needed not only to prevent the generation of pore pressure in specimen and to maintain the test in drained condition, but also to do the test in static condition and to eliminate the damping effect of plastic concrete.

To verify the saturation of the specimens, which is necessary to do the permeability test, the evolution of pore pressure coefficient ***B*** was monitored while isotropic compression test.

$$\boldsymbol{B} = \Delta U / \Delta \sigma_3 \tag{1}$$

in which $\Delta\sigma_3$ is increment of confining stress and ΔU is increment of pore pressure. Fig. 3 shows the evolution of ***B*** value for one of the specimens at the end of the isotropic compression phase of triaxial test. It shows that the specimen is very close to fully saturated. After saturation of the specimens and during the isotropic consolidation, by applying a backpressure and when the flow rate reaches to a steady state, the coefficient of permeability of specimens is measured. The effect of confining pressure on permeability is subsequently discussed.

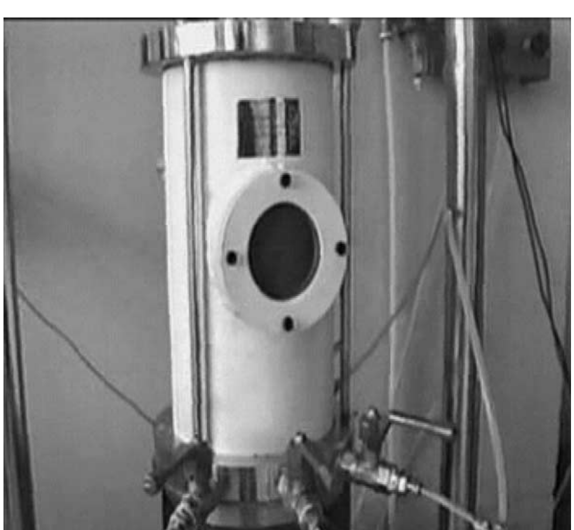

Fig. 2. Fabricated cell for the triaxial tests on plastic concrete specimens.

Consolidated drained tests have been done to study the effective parameters of mechanical behavior and permeability of plastic concrete. During the deviatoric test, the evolution of pore pressure is monitored and the strain rate is adjusted in such a manner to prevent the generation of pore pressure.

3. Influence of different parameters on mechanical behavior

3.1. Confining pressure

Fig. 4 shows the effect of confining pressure on the compressive strength of the specimens made from the mixes 4Z and R19. It can be clearly seen that the compressive strength increases considerably with an increase of confining pressure. The rate of this increase is almost the same for both specimens; however, the bentonite content and water–cement ratios are considerably different. The increase in confining pressure leads to a change in the mode of failure in the maximum load-carrying capacity. It can be seen that, at zero or low values of confining pressure, the behavior tends to be mainly brittle and the response exhibits a well defined peak and subsequent softening, whereas for the high confining pressures the behavior will be more ductile and axial and transversal strains of over 4% are obtained, and lead to horizontal plateaus. These results are similar to the results obtained by REMR [4] and Sfer et al. [7].

This type of behavior is common in cemented geomaterials and reported by other researchers [8,9]. In low values of confining pressure the failure mechanism will be governed by the progressive deterioration of the bonds between the aggregates, but in high values of confinements the shear strength will be mainly governed by frictional properties [10] (Fig. 5).

Fig. 6 shows the effect of confining pressure on the ratio of axial stress to confining stress (stress ratio) for mix 4Z at

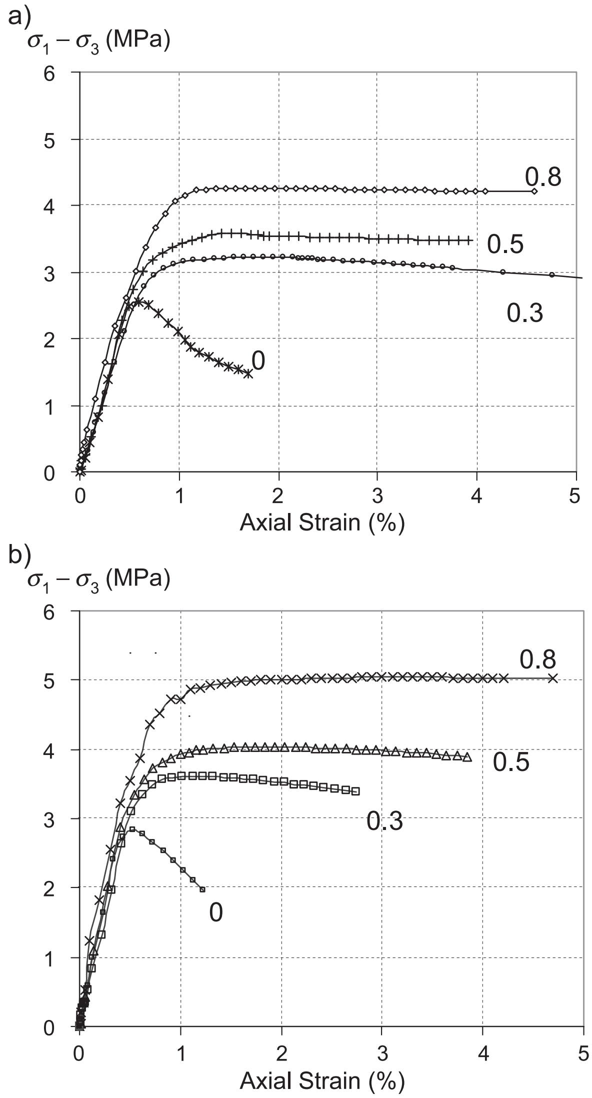

Fig. 4. Effect of confining pressure on unconfined and triaxial compression behavior of plastic concrete specimens; (a) specimen 4Z, (b) specimen R19, both in 28 days age.

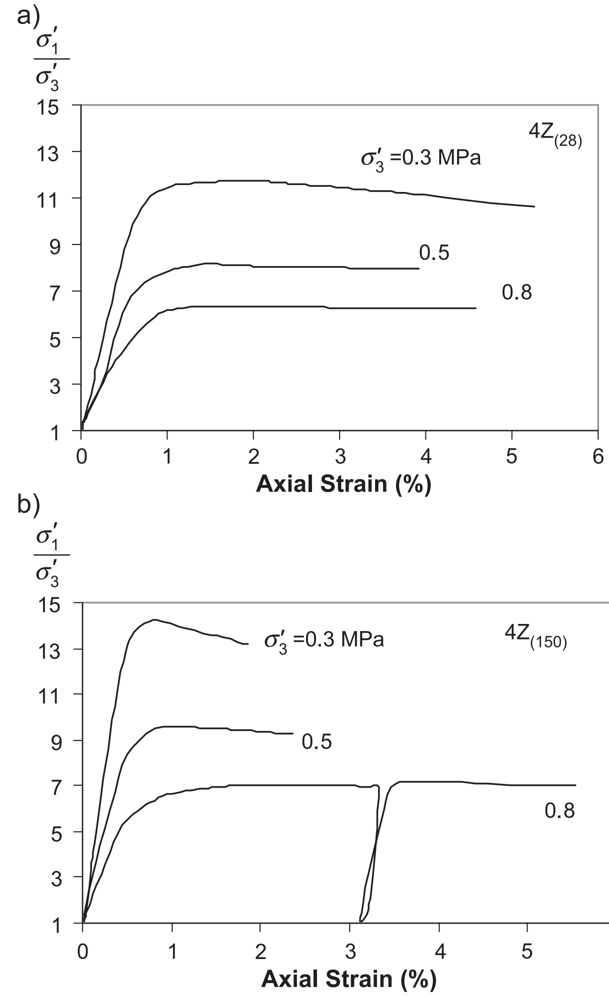

Fig. 6. Effect of specimens' age and confining pressure on the mechanical strength of plastic concrete, mix design 4Z (a) in 28 and (b) in 150 days.

ages 28 and 150 days. It shows clearly that stress ratio, σ_1/σ_3, is greatly decreases when the confining pressure increases. It is quite clear that the decreasing rate of stress ratio seems to be equal for 28 and 150 days specimens when confining stress increases.

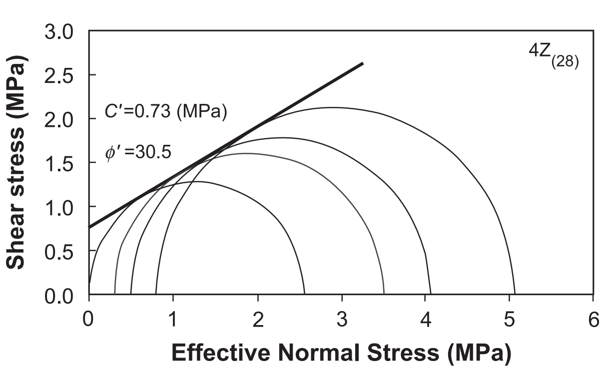

Fig. 5. Mohr envelope and the shear strength parameters for specimen 4Z (age of specimen: 28 days).

Bonded geomaterials, such as artificially cemented soils, can be classified between rocks and soils [11–14]. The mechanical behavior is governed by the friction between the aggregates and also by the bonds between the aggregates due to artificial cementation. Therefore one can consider bonded geomaterials, such as plastic concrete, which its compressive strength is comparable with the hard soils, as cohesive-frictional materials and coulomb type behavior can be admitted for them [10,15].

Figs. 5 and 7 show the Mohr envelope circles drawn for the triaxial test on specimens made from mix design 4Z at ages 28 and 150 days. By admitting the coulomb failure criterion for plastic concrete, the effective shear strength parameters, internal friction angle, ϕ' and cohesion, c', were obtained.

Fig. 8 shows the effect of confining pressure on elastic modulus of the different mixes of plastic concrete. It shows that increasing the confining pressure increases the elastic modulus and the rate of increasing is different and it depends

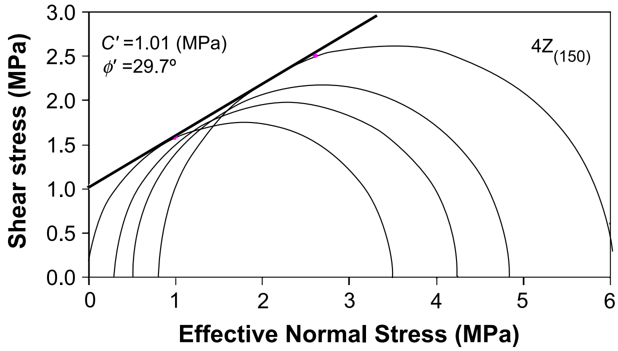

Fig. 7. Mohr circles and the shear strength parameters for mix design 4Z (age: 150 days).

on the cement factor, bentonite content and the age of specimens. The increasing rate of elastic modulus is higher for specimens with lower bentonite content (0.14 and 0.16). It can be justified by higher rigidity produced in specimens by reducing the bentonite content in mixtures. For the mixtures with higher values of B/C, this evolution is not significant.

3.2. Age of specimens

Figs. 6, 8 and 9 show the effect of the age of the specimens on mechanical behavior of plastic concrete. From Fig. 6, it can be concluded that, in general, for the tests with the same confining pressures, the peak or maximum value of stress ratio (or axial stress) increases with an increase of the age of the specimens. This phenomenon is more evident in low confining pressures.

Fig. 8 shows that the elastic modulus of plastic concrete specimens increases with an increase of the age of the

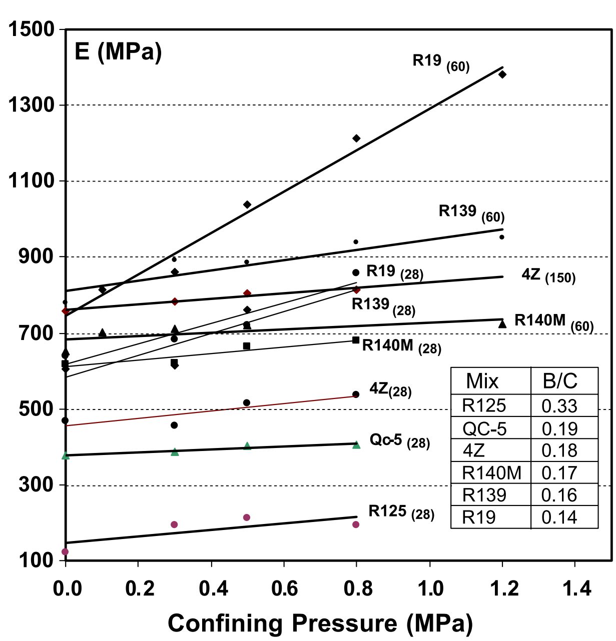

Fig. 8. Effect of confining pressure on elastic modulus evolution (subscripted numbers show the age of the specimens).

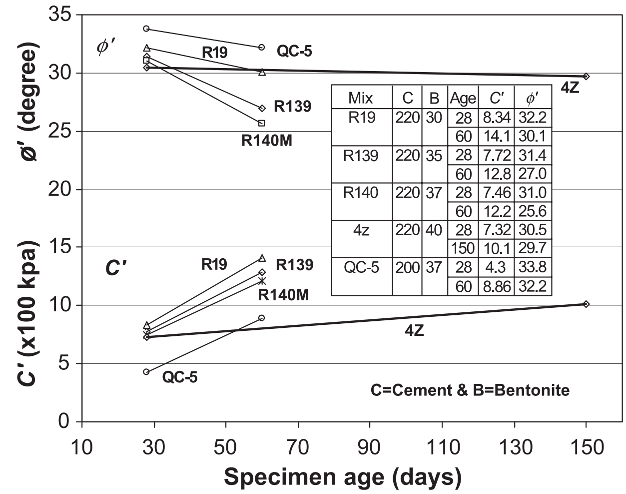

Fig. 9. Effect of specimens' age on the shear strength parameters.

specimens. It also shows that when the age of the specimens increases, the elastic modulus augmentation is almost equal for different confining pressures.

The evolution of shear strength effective parameters, ϕ' and c', with the age of the specimen are shown in Fig. 9. It can be clearly seen that when the age of the specimens increases, cohesion parameter increases and the internal friction angle slightly reduces. Therefore, it can be concluded that the increase of the compressive strength of plastic concrete due to the completion of the cement hydration and the strengthening of the bonds between cement paste and aggregates is reflected on the shear strength parameters by increasing the cohesion parameter, although the internal friction is slightly reduced. The same trend of evolution of the shear strength parameters of concrete as a function of its compressive strength was noted by Nielsen [15]. The rate of augmentation of the cohesion or decrease of the internal friction is smaller for the mix 4Z, which its water–cement ratio is greater than other specimens shown in Fig. 9.

3.3. Cement factor and water–cement ratio

The effect of cement factor on shear strength parameters of plastic concrete is shown in Fig. 10. It shows that increasing in cement factor increases the cohesion parameter and lightly reduces the internal friction angle of the material. This effect does not have the same intensity for the different mixes. The same results were obtained and shown in Fig. 11 by plotting the evolution of shear strength parameters versus water–cement ratio of the specimens.

As for a normal concrete, the compressive strength depends on the cement factor as well as the water–cement ratio. With increasing the cement factor or decreasing water–cement ratio, the compressive strength increases. Fig. 4 shows clearly this effect of water–cement ratio evolution on the compressive strength for the specimens 4Z and R19. Generally, obtained results show that an increase

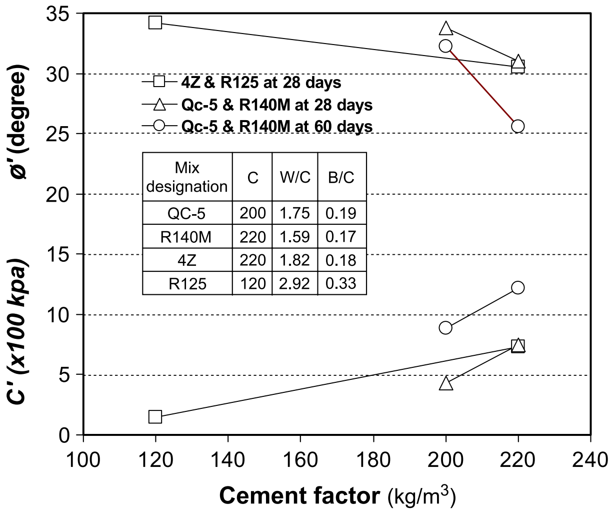

Fig. 10. Effect of cement factor on shear strength parameters of plastic concrete.

of 10% in cement factor leads to an increase of 50% in simple compression strength.

For the unconfined compression test, the same increase of 10% in cement factor causes 40% increase of elastic modulus and in the case of triaxial test an increase of 20–50% of elastic modulus is obtained (Fig. 8).

3.4. Bentonite content

Effect of the bentonite content on the mechanical behavior of plastic concrete is shown in Figs. 8, 12 and 13. Fig. 12 shows the evolution of the compressive strength of the specimens, R19, R139 and R140M, that the difference between them is only their bentonite contents. It shows that when the bentonite content increases the compressive

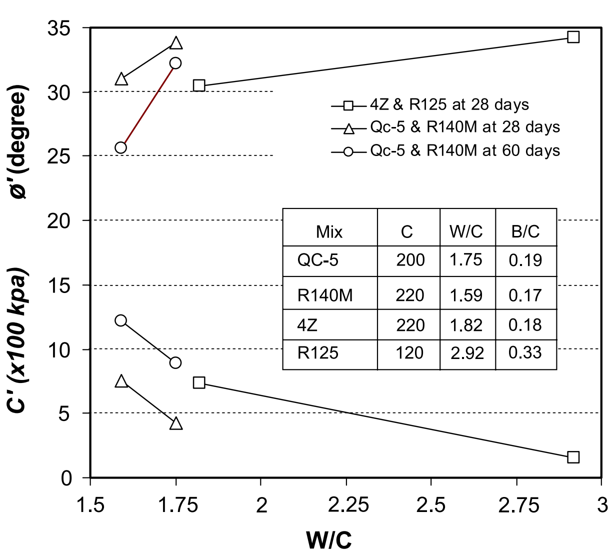

Fig. 11. Effect of water–cement ratio on shear strength parameters of plastic concrete.

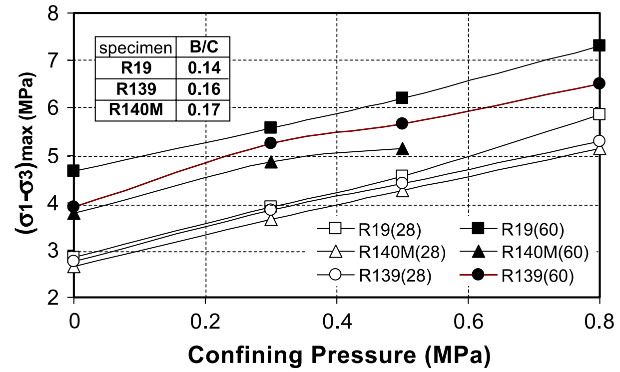

Fig. 12. Effect of bentonite content variation on the compressive strength of plastic concrete specimens for different confining pressures.

strength of the plastic concrete specimens decrease and this reduction is more important when the age of the specimens increases. As explained before, this reduction is due to the higher bentonite content that lessens the bonding between the aggregates and cement paste.

Fig. 8 shows that the elastic modulus was also affected by the bentonite content. Evolution of the elastic modulus of the mentioned specimens, plotted in Fig. 8; show that when the bentonite content of the specimens increases the elastic modulus decreases and the difference between the elastic modulus of the different specimens is more important when the age of the specimens increases. For the mentioned specimens, elastic modulus obtained in a simple compression test, reduced up to 36% and modulus obtained in triaxial tests are reduced up to 60% that depends on confining pressure (Fig. 8).

Fig. 13 shows the effect of bentonite content on shear strength parameters. It shows that the shear strength parameters are also affected. When bentonite content increases, the cohesion and the internal friction angle decrease. It seems that the decreasing slope of the cohesion and internal friction angle are constant. These slopes are steeper when the age of the specimens increases.

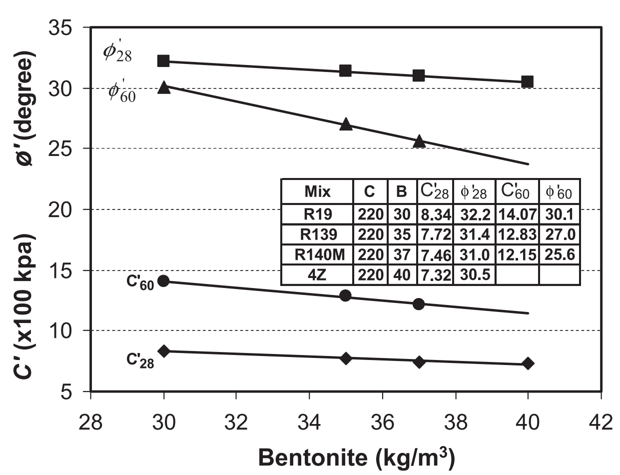

Fig. 13. Effect of bentonite on shear strength parameters of plastic concrete.

4. Permeability of plastic concrete

A plastic concrete cut-off wall can hardly stop all the seepage under the dam completely, but it can simply prevent excessively high discharges. The overall permeability of a plastic concrete cut-off wall depends partly on the intrinsic properties of material, and partly on the possible existence of major flaws such as: discontinuities in wall, poor placing method, etc.

In practice, the permeability of plastic concrete will be of the order of 10^{-8} to 10^{-9} m/s [3]. Because of the importance of permeability of plastic concrete in its usage, the effects of the different parameters on permeability have been studied.

4.1. Effect of confining pressure on permeability

The effect of confining pressure on the permeability of plastic concrete is shown in Fig. 14. It can be concluded that increasing the confining pressure decreases the permeability of the specimen. This decrease in specimen permeability can be justified by the closing of the pores in the specimen due to high confining pressure. It is shown that for the two specimens of the mixture R139 with different ages, 28 and 60 days, the coefficient of permeability reaches, approximately, to a unique value at higher confining pressure. Therefore it can be concluded that at high confining pressure, the permeability is independent of the age of the specimens.

4.2. Effect of cement factor on permeability

The effect of cement factor on permeability is shown in Fig. 15. It shows that with increasing cement factor the permeability is reduced. It can be justified by the absorption of the mixed water by cement and therefore less free water to produce the voids, which is the main cause of concrete permeability. The permeability of the mix with smaller cement factor is higher than that of the other specimens shown in Fig. 15, because the free water in specimen produces the voids in concrete and by increasing the void ratio the permeability increases; since concrete workability is intended, therefore there is some free water in this concrete.

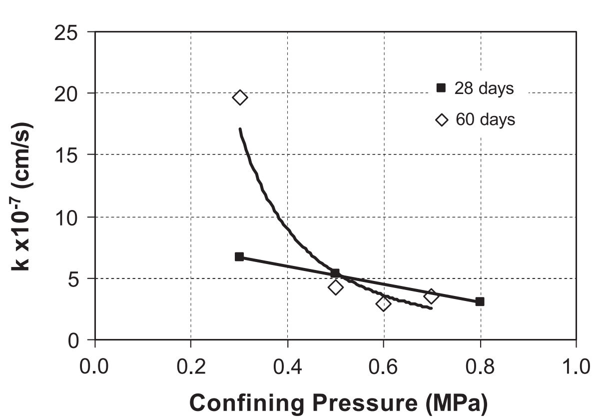

Fig. 14. Effect of confining pressure on the permeability of mixture R139 in 28 and 60 days, correlation line and curve are shown.

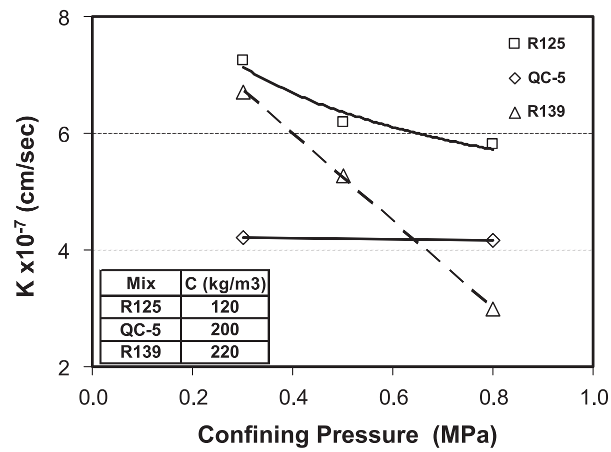

Fig. 15. Effect of cement factor on the permeability of plastic concrete specimens (age of specimens 28 days).

4.3. Effect of bentonite content on permeability

The effect of bentonite content on permeability is shown in Fig. 16. It shows that increasing bentonite content results in decreases the permeability of the specimen. Generally the results of this study and another one [4] show that increasing the bentonite content initially reduces the permeability but after a specific bentonite content because of increasing the water required in the mixture to maintain concrete workability, the dry density decreases and the permeability increases. The increased water tends to counterbalance the increased bentonite.

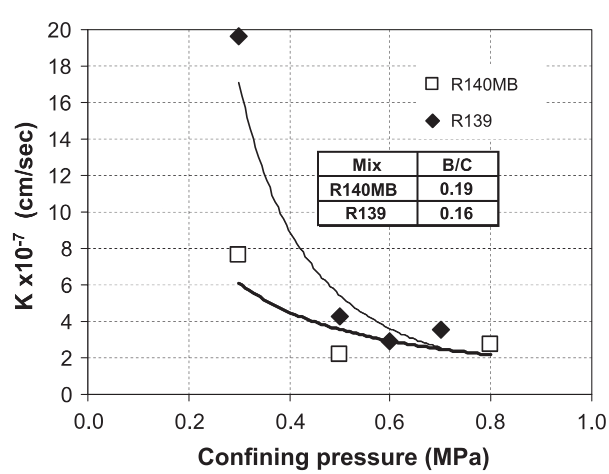

Fig. 16. Effect of bentonite content on the permeability of plastic concrete specimens (age of specimens 60 days).

5. Conclusion

Mechanical behavior and the permeability of plastic concrete in unconfined and triaxial state condition were studied. The effect of specimen age, cement factor, bentonite content and confining pressure on the mechanical behavior and permeability of plastic concrete were investigated.

It is obtained that shear strength increases with the age of the specimens. The shear strength parameters, cohesion and internal friction angle, are affected by the age of the specimens. The cohesion increases with the age of the specimens but the internal friction angle decreases. The elastic modulus of the specimens increases with the age of the specimens.

Increasing confining pressure increases the compressive strength as well as the elastic modulus. Also increase of confining pressure increases the strain corresponding to failure of the specimen and turns its behavior more ductile.

It is concluded that an increasing cement factor and decreasing water–cement ratio results in increasing compressive strength and elastic modulus. The shear strength parameters are affected, also. The cohesion increases with the cement factor and the internal friction angle slightly reduces.

Bentonite lessens the rate of the chemical reactions of cement hydration in plastic concrete and the rate of strength increasing is lower than that of normal concrete. Increasing the bentonite content reduces the compressive strength and shear strength parameters. Elastic modulus is also reduced by the increasing of the bentonite content.

It is shown that increasing the confining pressure and cement factor reduces the permeability. Also increasing bentonite content reduces the permeability, but there is a threshold for bentonite content beyond which the permeability is not greatly lowered. This threshold for bentonite content depends on the bentonite properties and its composition.

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