EFFECTS OF DIFFERENT CONSTITUENT MATERIALS ON THE PROPERTIES OF PLASTIC CONCRETE

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Abstract: *Having observed the costly failures of different cutoff walls, that had been constructed according to the mix design specified by reputable consultants in Iran, a research programme was conducted to study the effects of constituent materials on the properties of plastic concrete. The main properties, such as compressive strength, biaxial and triaxial strains, permeability, and modulus of elasticity have been investigated using different mixes, obtained from prototype production line plant, situated on site, because it was realized that the site production line and the systems employed have major effects on the properties of plastic concrete. Statistical analysis of the results, revealed the coefficients of influence of main constituent materials of plastic concrete namely cement, bentonite, aggregate and water on its compressive strength and modulus of elasticity. Having realized the cancelling effects of bentonite and aggregates on the measured properties, some equations relating the quantities of cement and water to the compressive strength and modulus of elasticity are introduced. Effects of clay and hydrated lime powder, as fillers were also investigated leading to the proposal of limits for their safe and economic use. Since most of the cutoff walls are buried structures, failure strains under both uniaxial and triaxial tests, with values of cohesion and internal friction, are also presented in this paper.*

Keywords: *Plastic concrete, Cut-off wall, Concrete dam, Bentonite, Filler.*

1. INTRODUCTION

Seepage control is critical to the safe operation of dams and has always created serious challenges for engineers. Therefore, many researchers have investigated the materials and the methods employed in the construction of cutoff walls, the results of which have been presented in different seminars and conferences organized by International Commission on Large Dams (ICOLD), since 1970 [1].

While remedial seepage control can be achieved with a rigid concrete cutoff wall, deformation of the earth embankment can cause the concrete wall to rupture. Therefore, materials selected for construction of cutoff walls must be strong and watertight and have stiffness comparable to the surrounding embankment 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. Although many research programs have resulted in some solutions to the above mentioned problems by giving suggestions on practical aspects of concrete cutoff walls, but they seem to be inadequate for different site and material conditions [2, 3, 4, 5, 6].

During the construction of the largest dam in Iran, after successive and very costly failures of different cutoff walls, constructed according to the mix design shown in Table 1, which had been proposed by reputable consultants, a comprehensive research work was conducted at Imam Khomeini International University during which, different methods of construction of concrete cutoff walls and their plastic concrete constituent materials, used in different dams were carefully studied and many trial mixes were made, but the results were unsatisfactory [7]. Since the production of plastic concrete and the plant used, depends on the method of the construction and the required functions of the cutoff walls, 225 different plastic concrete mixes were made during 120 days of the investigation. About 182 mixes were prepared for studying the effects of changes in the amount of cement, bentonite, water, types of aggregate (crushed and uncrushed), and the rest were used for permeability, biaxial and triaxial tests. The properties measured included: compressive strength, static modulus of elasticity, permeability, internal friction angle, cohesion and strain under both biaxial and triaxial loading systems. Having noticed the importance of different fillers, the effects of clay and hydrated lime powder were also investigated [8].

Table 1. Primary mix design of plastic concrete.

Cement (kg)	Bentonite (kg)	Aggregate (kg)			W/C	Slump (mm)
		0-5 mm	5-9.5 mm	9.5-19 mm		
220	37.5	705	495	300	1.58-1.62	180-200

Knowing that the different cutoff walls are used for different purposes constructed out of different materials such as: bentonite mud + fine and coarse aggregates (for up to 25m depth, and 3m thickness) or: bentonite mud + cement (for the thickness of up to 1.5m), all of which are employed for jobs with less importance, this investigation aimed at providing necessary information on cutoff walls with more than 50m depths and 0.6m to 1.2m thickness [9, 10]. Construction of these cutoff walls include cutting the ground and then filling the excavated area by tremie method using ordinary or plastic concrete for its inherent advantages.

Study of the recorded experiences on the use of plastic concrete in Iran, showed that the employed plastic concrete in Mahabad and Panzdahe Khordad dams had been made by mixing sand, clay and cement, and the depths of the constructed cutoff walls were less than 20m, indicating their less significance [8]. But in the proposed dam, a cutoff wall with the depth of over 75 meter with the length of about 2700 meter was required. The dimensions of this wall not only show its importance but also indicates the lack of any practical experience for the construction of a cutoff wall of this size in Iran. Although the examination of the related information on Conventoviejo dam in Chili [11], Wister dam in U.S.A [12], and studying the compatibility of cement/bentonite cutoff walls [13, 14], provided us with some useful data on the mix design of the required plastic concrete, but unfortunately the cutoff wall designed and constructed on the basis of above mentioned information, also failed by numerous random cracking. The widths of the cracks ranged from 5mm to 90mm and they were located at different levels.

For the environmental conditions and specified production line, about 245 different mix designs were made and the required properties were measured. Having got the experimental data, statistical analysis of the data were carried out and the most suitable mix design for different purposes were identified.

2. DEFINITION OF PLASTIC CONCRETE AND PROPERTIES OF CUTOFF WALLS

Plastic concrete which is sometimes referred to as low strength concrete or artificial soil consists of aggregate, cement, water, and bentonite clay mixed at a high water-cement ratio to produce a ductile material. Plastic concrete is also used for control of infiltration of harmful sewage and the penetration of seawater, and more recently for filling the surrounding of water ducts in power plants. Plastic concrete shows great promise for satisfying the strength, stiffness, and permeability requirements for remedial cutoff wall construction.

The cutoff wall made out of plastic concrete, should exhibit the following properties:

a) With regard to the permeability, K in Darcy's equation should be within 10^{-8}-10^{-7} m/s.
b) Deformations resulting from foundation

and dam settlements, vertical and horizontal displacements, resulting from the first filling of the dam, and changes in the water level, should be safely withstood without cracking.

c) Vertical and horizontal displacements, resulting from the first filling of the dam, and changes in the water level, should be safely withstood without cracking.
d) Compressive strength of the in-situ concrete has to be of such a magnitude that, the weight of the dam and the stresses induced from surrounding soil and rock at different depths, should not cause any cracking.
e) Regarding the corrosive solutions in the water, such as acids, sulfates etc., be durable for its design life.
f) The method of construction should be such that, to avoid early setting of fresh plastic concrete and in order to use the tremie method effectively, fresh plastic concrete should have the necessary workability.

3. MATERIALS AND METHODS

Since the production of the plastic concrete on site has its own procedure which comprises of saturated slurry, plastic grout and plastic concrete productions, and for the fact that, each and every step in the production line can have serious effect on the properties of final plastic concrete, therefore, with all the experiments, it was decided to use mixes produced by the prototype plastic concrete production plant on site.

3.1. Materials

Selection, proportioning and mixing of plastic concrete constituent materials should be such that the required flexibility, impermeability, resistance to wear, and compressive strength be achieved using the specified equipment and plant. The cement employed was internally produced sulfate resisting portland cement, and the bentonite used was of calcium montmorillonite type 2, and was saturated according to ICOLD recommendations. Natural sand was chosen as fine aggregate, and the coarse aggregate included both crushed and uncrushed types, with 20mm maximum size. Hydrated lime powder and clay were also used as fillers.

3.2. Mix proportions

According to ICOLD recommendations, for the mix designs considered, the quantity of cement ranged from 120 to 280 kg/m^3 and that of bentonite was 15 to 70 kg/m^3. When considering the effects of clay and hydrated lime powder as fillers, their respective quantities ranged from 50 to 200 kg/m^3 , for clay and 100 to 150 kg/m^3 for hydrated lime powder. The quantity of aggregate was kept between 1400 and 1600 kg/m^3 and the employed w/c ratio was between 1.13 to 3.25.

Table 2. Crystalization of bentonite in sodium chloride solution.

NaCl (%)	Aging time (h)	PH	Viscosity (cps)	Thixotropy		API FL* (cc)
				1 gs	10 gs	
0	24-144	9	11.8	5	15	15
0.25	24-144	8.85	11	35	40	18
1	24-144	8.40	8.4	20	25	21
5	24-144	8.35	3.2	5	10	99
15	24-144	8.05	3.2	5	10	180
30	24-144	7.60	3.2	5	10	180

*American Petroleum Institute – Fluid Loss

3.3. Test Methods

3.3.1. Tests on constituent materials

Since the quality of the bentonite used in plastic concrete plays a major role in its final properties, necessary chemical and physical experiments were carried out on the employed bentonite in accordance with the American Petroleum Institute (API) [15, 16] recommendations and some of the results are tabulated in Table 2. Determination of the liquid limit of bentonite used, was conducted according to Deutsches Institute fur Normung ev (DIN) [17] recommendations, using sphere shearometer, but for brevity the results are not presented here. Tests for ensuring the quality of cement were carried out in accordance with American Society for Testing and Materials (ASTM) [18]. Based on the recommendations made by ICOLD, the aggregates were grouped into three categories according to their sizes, namely 0-5mm, 5-9.5mm and 9.5-19mm. Different tests were carried out on aggregates according to ASTM standards which included C289 (alkali reaction), C123, C142, C351, C117 (harmful elements), C127, C128 (chemical analysis), C136 (particle size distribution) and C70 (moisture content) [18,19].

3.3.2. Tests on plastic concrete

Since the workability of the plastic concrete is of great importance, the slump of five different mix designs at different time intervals which ranged from 250 mm (after mixing) to about 50 mm (after three hours) are plotted in Fig. 1. From this figure it can be seen that the rate of decrease in the slumps of all mixes considered are almost uniform (about 1mm/min). Therefore, regardless of the mix proportions, it is possible to forecast the flowability after specified time and under different site conditions. It should be noted that, since the stiffening and hardening (gaining strength) of a concrete cannot be predicted from the setting time of its cement, the workability of the concrete itself should be assessed under working conditions with respect to the plant used.

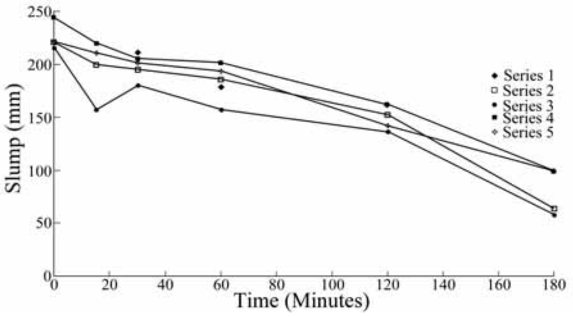

Fig. 1. Slump of different mix designs at different time intervals.

Preparation of plastic concrete samples and determination of its specific gravity were conducted according to ASTM standards sections C1064, C172, C138, C192. In determining compressive strength, the rate of application of the load was based on 0.4 mm/min as jig travelling rate, which was selected according to DIN recommendations. Triaxial compressive tests were carried out in accordance with ASTM, D2850 and American Association of State Highway and Transportation Officials (AASHTO) [20], T234 standards under UU (unsaturated undrained) conditions. The values chosen for δ_3 (lateral pressure) were 0.3, 0.5 and 0.7 N/mm^2 and the rate of loading was based on the jig travelling rate of 0.3mm/min, and from the resulting Mohrs circles, different values for cohesion and friction angle were calculated. The permeability tests were carried out according to DIN 1048 using 150×300mm cylindrical samples at the age of 28 days. Determination of static modulus of elasticity were conducted in accordance with ASTM C469 standard with 1.25mm/min as the jig travelling rate.

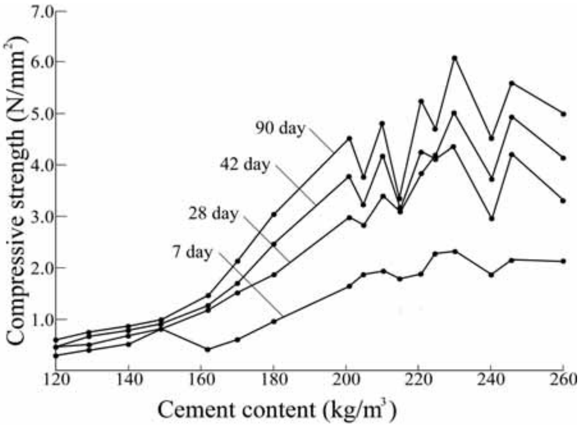

Fig. 2. Compressive strength of different mixes at different ages.

4. RESULTS AND DISCUSSION

4.1. Uniaxial Tests

Changes of compressive strength and the modulus of elasticity with changes in cement and bentonite content at the ages of 7, 28, 42 and 90 days are shown in Figs. 2-5. It can be seen from Fig. 2, that for the ages considered, the increase in the amount of cement from 120 to 220 kg/m^3, increased the compressive strength and modulus of elasticity, but beyond 220 kg/m^3 cement content, these increases are not significant. It should also be noted that, increasing the quantity of bentonite from 15 kg/m^3 to about 28 kg/m^3, causes the compressive strength and modulus of elasticity increase, but when bentonite increases beyond about 30 kg/m^3, these parameters are decreased. It should also be pointed out that, the unit weight decreased with increase in the bentonite content. Considering the effect of aging, it is seen that, the changes for the properties considered are more significant for the age of 28 days.

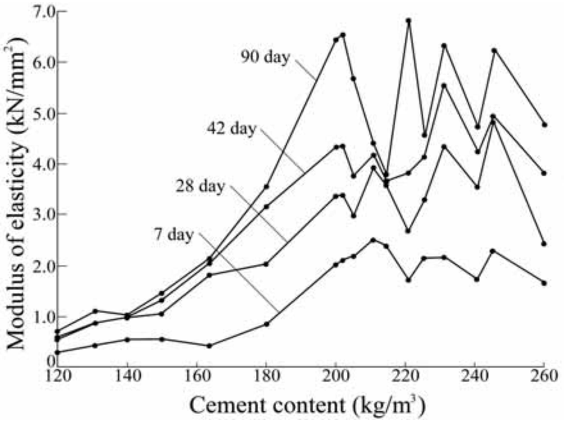

Fig. 3. Modulus of elasticity of different mixes at differe ages.

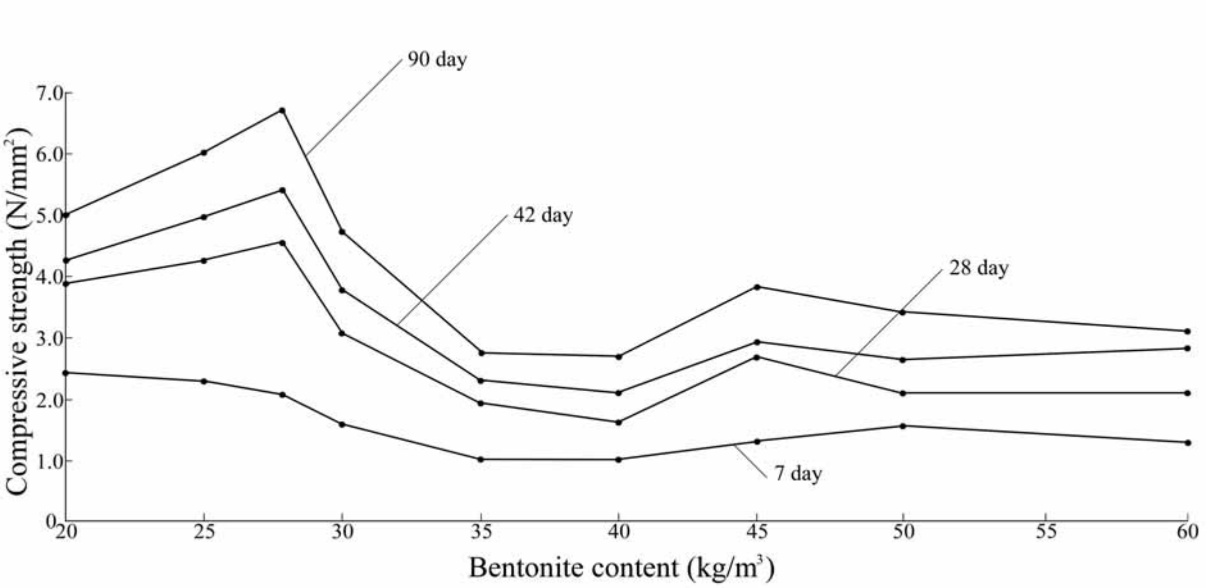

Fig. 4. Effect of bentonite content on compressive strength, at different ages.

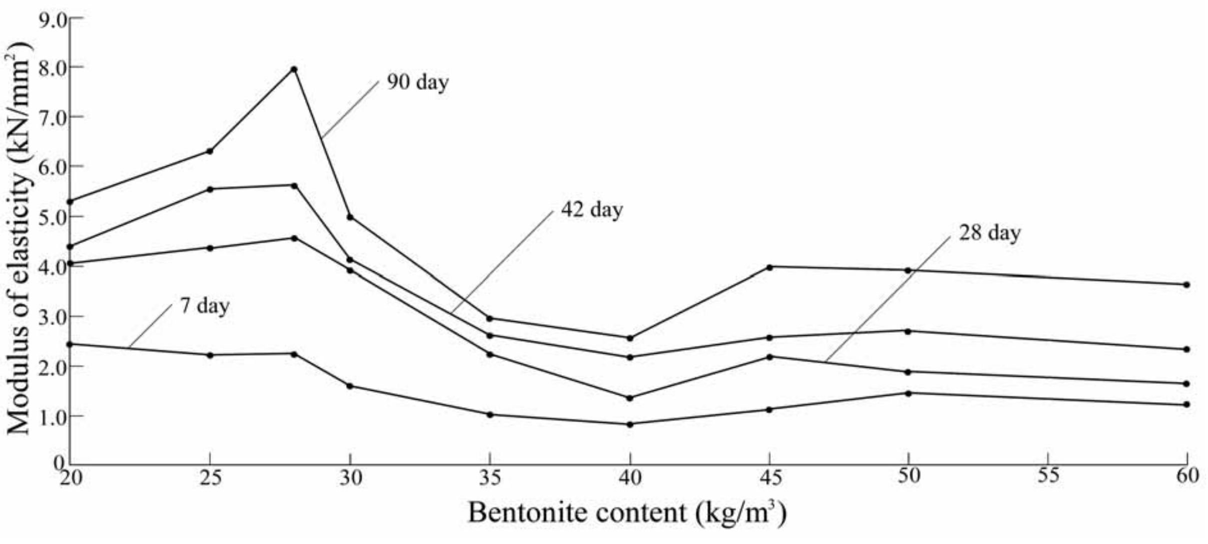

Fig. 5. Effect of bentonite content on modulus of elasticity, at different ages.

4.2. Triaxial Tests

Considering the results presented in section 3.1, and due to the significant effect of 200 kg/m^3 cement content, in the mixes prepared for triaxial tests, the quantity of cement was kept constant at this level. Based on the information obtained from ICOLD and the detailed studies of some related technical documents[2-7], the lateral pressures chosen for this part of experiments, were chosen as 0.3, 0.5 and 0.7 N/mm^2 and the age of the specimens at the time of testing was 28 days. Having drawn the Mohr's circles, cohesion and friction angles were calculated and with their related bentonite contents are shown in Figs. 6 and 7. As it can be seen from these results, increasing the bentonite content of the plastic concrete from 20 kg/m^3 to 60 kg/m^3, displays positive effect on internal friction angle which increases from about 5^0 for 20 kg/m^3 bentonite content, to about 40^0 for 60 kg/m^3 bentonite content. Considering the effect of bentonite content on cohesion, it can be seen that, increasing the bentonite content causes reduction in cohesion values up to about 35 kg/m^3 bentonite content, but it remains almost steady at about 0.3 N/mm^2 for bentonite content of up to 60 kg/m^3 and after this value, it tends to increase.

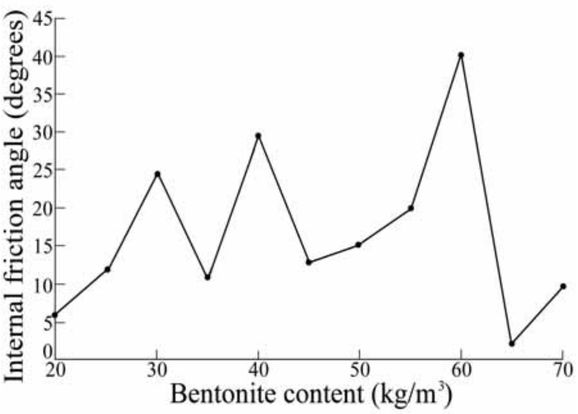

Fig. 6. Effect of bentonite content on internal friction angle.

Comparison of the behavior of plastic concrete under triaxial and biaxial tests showed that, in triaxial test the failure strain reaches about 0.006 compared with the respective value of 0.002 in biaxial test. It was also observed that, the increase in lateral pressure, caused reduction in the failure strain under triaxial test. Since most of the structures constructed using plastic concrete are buried, when studying the plastic concrete behavior, the use of triaxial test appears to be more appropriate.

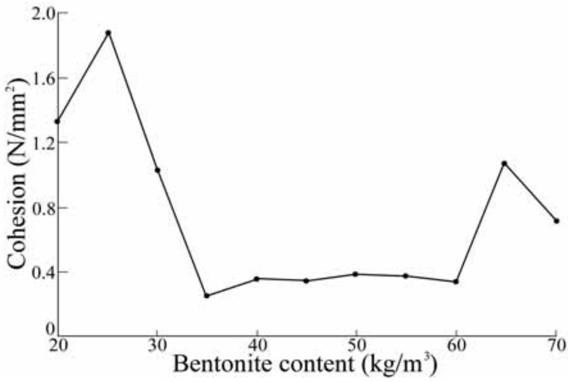

Fig. 7. Effect of bentonite content on cohesion.

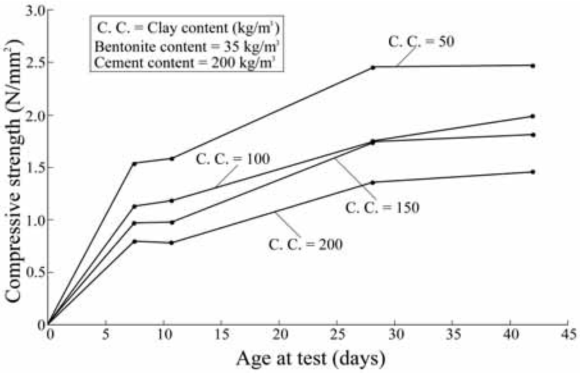

Fig. 8. Effect of clay content on compressive strength, with specified amount of bentonite and cement contents, at different ages.

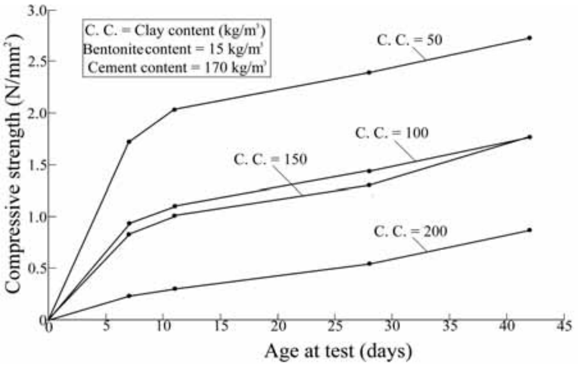

Fig. 9. Effect of clay content on compressive strength, with specified amount of bentonite and cement contents, at different ages.

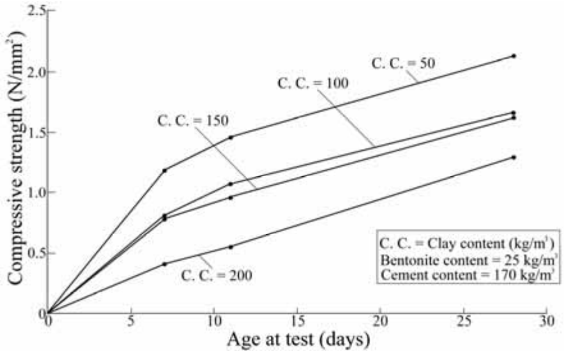

Fig. 10. Effect of clay content on compressive strength, with specified amount of bentonite and cement contents, at different ages.

4.3. Effects of Filler

In the production of plastic concrete, when some required properties are not achievable by changing the quantity and/or proportions of its main constituents namely cement, bentonite and aggregates, addition of fillers such as hydrated lime powder, clay etc. are considered.

From the results shown in Figs. 8, 9 and 10 with 15, 25 and 35 kg/m^3 respective bentonite contents, it can be seen that increasing the clay content, reduces the compressive strength, but for the range of 100-150 kg/m^3 clay content, its effect on the compressive strength is almost negligible, indicating that 150 kg/m^3 clay content may be considered as an optimum value. Examination of the results obtained for modulus of elasticity, reveals that, the effects of different clay content on the modulus of elasticity is similar to those observed for the compressive strength. The results of the inclusion of hydrated lime powder as filler are shown in Figs. 11 and 12. From these Figures it can be seen that the addition of hydrated lime powder makes all the curves of compressive strength and modulus of elasticity converge, suggesting that due to the binding effect of the hydrated lime powder, the increases in the cement quantity has no significant effect on the two parameters considered, provided that the quantity of the filler is kept at about 100 kg/m^3. Therefore, since the cement is more expensive than hydrated lime powder, inclusion of this filler due to its binding effect is more economical.

4.4. Permeability Tests

Permeability tests were carried out on 28 day old specimens only. From the results obtained, it was observed that the presence of bentonite significantly decreases the permeability and the K values measured ranged from 9.7 × 10^{-7} to 1.22 × 10^{-10} which lies within the acceptable limits. Although the general tendency of the results showed decreasing effect of the quantity of bentonite on permeability, but it was not possible to define a constant relationship between the variables involved. This is possibly due to the effect of bentonite/water and w/c ratios as well as the effects of the fillers.

4.5. Effects of Constituent Materials

In order to find the effect of constituent materials namely cement, bentonite, aggregate and water on compressive strength and modulus of elasticity of plastic concrete, Tables 3 and 4 were prepared using the statistical analysis of the experimentally measured values. Results shown in these tables reveal that, the cement has a positive effect of 45 to 51 percent on the 7 and 28 day compressive strengths respectively, but this effect is reached about 57 percent for the age of 90 days. The respective values for the modulus of elasticity is shown to be 33, 44 and 56 percent.

Table 3. Coefficients of influence of different constituent materials on compressive strength (%).

Age (days)	Cement	Bentonite	Aggregate	Water
7	+45.31	-14.35	+15.32	Negligible
28	+51.11	-23.38	+31.65	Negligible
42	+50.86	-28.83	+30.75	Negligible
90	+57.26	-28.86	+27.87	-18.63

Table 4. Coefficients of influence of different constituent materials on modulus of elasticity (%).

Age (days)	Cement	Bentonite	Aggregate	Water
7	+32.50	-16.28	+28.27	Negligible
28	+44.08	-29.29	+28.62	-23.74
42	+33.38	-23.71	+20.93	-25.52
90	+55.65	-33.78	+17.54	-26.33

With regard to the aggregate content, it can be seen from Table 4 that, aggregate has a positive effect on both compressive strength and modulus of elasticity of plastic concrete with the respective values of 15, 32, 31 and 28 percent on compressive strength and 28, 29, 21 and 18 percent on the modulus of elasticity for the respective ages of 7, 28, 42 and 90 days.

The same results show that for the effect of water content on the compressive and modulus of elasticity of plastic concrete, meaningful interpretation is not possible. This can be due to the negative effect of bentonite which unlike ordinary concrete cases, makes the prediction of the effect of w/c ratio difficult.

In an attempt to establish the relationships between the quantity of main constituent materials of plastic concrete and its compressive strength and modulus of elasticity, statistical analysis resulted in the equations shown in Table 5.

Table 5. Coefficients of equations relating compressive strength and modulus of elasticity of plastic concrete with its cement and water contents at different ages.

Age (days)	Measured property	Coefficient of cement content	Coefficient of water content	Constant
7	Compressive strength (N/mm^2)	+0.01208	-0.00266	+0.01821
28	Compressive strength (N/mm^2)	+0.02316	-0.00563	+0.02439
42	Compressive strength (N/mm^2)	+0.02551	-0.00585	+0.15758
90	Compressive strength (N/mm^2)	+0.03136	-0.00866	+0.61176
7	Modulus of elasticity (kN/mm^2)	+0.011413	-0.003409	+0.55000
28	Modulus of elasticity (kN/mm^2)	+0.022869	-0.008999	+1.50493
42	Modulus of elasticity (kN/mm^2)	+0.018465	-0.009426	+3.31298
90	Modulus of elasticity (kN/mm^2)	+0.032322	-0.011567	+1.88651

From the coefficients presented in Table 5, it can be seen that the multiplier of cement for 42 day modulus of elasticity doesn’t follow the same increasing pattern of other multipliers, indicating that at least for some ages, the relationships between the compressive strength and the modulus of elasticity of plastic concrete are not of a predefined form.

Examination of these equations also reveal that, due to the cancelling effect of bentonite and aggregate coefficients on each other, the best estimates of compressive strength and the modulus of elasticity of plastic concrete may be obtained by considering the quantity of cement and water in the mix only. This may be attributed to the fact that, the continuation of hydration process of cement is responsible for the strength gained.

5. CONCLUSIONS

Considering the results of the investigations presented in this paper, the following conclusions are drawn:

1. The ranges of the compressive strength and the modulus of elasticity of plastic concrete, lies within the respective ranges of disturbed soil and ordinary concrete.
2. Bentonite as one of the constituent materials of plastic concrete enhances its impermeability, and the K values measured ranged from 9.7×10^{-7} to 1.22×10^{-10} which are within the acceptable limits recommended by ICOLD.
3. The internal friction angle was shown to increase with the increase in bentonite content, reaching about 40^o for the bentonite content of 60 kg/m^3. By increasing the bentonite content, the cohesion of plastic concrete decreased but when the bentonite content reached the value of 35 kg/m^3, the cohesion remained steady at about 0.3 N/mm^2 for higher contents of bentonite.
4. Increase in the clay content as filler in

plastic concrete, reduced its compressive strength and the modulus of elasticity, but for the ranges of 100-150 kg/m^3 clay content, this reduction was not significant, indicating the above mentioned values as the optimum values for clay content.

5. Inclusion of hydrated lime powder in plastic concrete, reduces the effect of cement content on the compressive strength and the modulus of elasticity, due to its own binding properties. When the content of hydrated lime powder was kept at about 100 kg/m^3, increase in the cement content showed no significant effect on the compressive strength and the modulus of elasticity of plastic concrete. Therefore, for economical purposes, hydrated lime powder can replace the cement content in plastic concrete without showing adverse effect on the compressive strength and the modulus of elasticity of plastic concrete.
6. Statistical analysis of the results, showed that, the cement content has a positive effect of 45, 51 and 57 percent on 7, 28, and 90 day compressive strength of plastic concrete respectively. The respective values for the modulus of elasticity were shown to be 33, 44 and 56 percent.
7. Linear equations relating the compressive strength and modulus of elasticity of plastic concrete with the quantities of its main constituent materials, for the ages of 7, 28, 42 and 90 days were identified, but they included the quantities of cement and water only.
8. Since most of the cutoff walls are buried structures, for examination of their in-situ concrete behaviour, the triaxial test is more appropriate. The failure strains obtained using triaxial tests were shown to be three times that of those obtained via biaxial test.

ACKNOWLEDGEMENTS

Thanks are due to the authorities of Imam Khomeini International University for the facilities provided for the experimental work of this research.

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