FRACTURE BEHAVIOR OF CONCRETES INCORPORATING BONE POWDER

سلوك الكسر للخرسانة المحتوية على بودرة العظم المطحون

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الملخص العربى

أصبح لاستخدام النفايات الناتجة من مخلفات المصانع أهمية كبيرة في السنوات القليلة الماضية. وقد تعرض هذا البحث لدراسة متانة الكسر للخرسانة المحتوية على بودرة العظم المطحون كنسبة إضافة من وزن الأسمنت ومقارنتها بالخرسانة المحتوية على السليكا فيوم كنسبة إضافة من وزن الأسمنت (١٠%). وقد تم دراسة أربعة أنواع مختلفة من خلطات الخرسانة وهى (الخلطة الأولى لا تحتوى على إي إضافة (M_I) – الخلطة الثانية تحتوى على نسبة إضافة ٥% من بودرة العظم (M_{II}) – الخلطة الثالثة تحتوى على نسبة إضافة ٥% من بودرة العظم و٥% من السليكا فيوم (M_{III}) – الخلطة الرابعة تحتوى على نسبة إضافة ١٠% من بودرة السليكا فيوم (M_{IV})). كما تم دراسة تاثير ثلاث أطوال مختلفة من طول الشرخ كنسبة من عمق الكمرة وهى ($a/w = 0.2, 0.3, 0.4$) لدراسة متانة الكسر لتلك الخلطات المذكورة. وقد تم أيضا فى هذا البحث دراسة الخواص الميكانيكية للأربعة الخلطات المذكورة. وقد أظهرت النتائج أن هناك زيادة ملحوظة فى مقاومة الضغط والشد للخلطة الثالثة المحتوية على نسبة إضافة ٥% من بودرة العظم و٥% من السليكا فيوم. كما وجد أيضا أن الخلطة الثالثة تعطى أعلى مقامة للكسر بمقارنتها بالخلطات الأخرى. ووجد أيضا أن مقاومة الكسر تقل مع زيادة نسبة a/w .

ABSTRACT

Using of wastes and by-products in the concrete has attained great potential in the last few years. This study investigates the use of bone powder as addition of cement and the influence of the bone powder content on the fracture behavior of concrete beams. All beams containing bone powder were compared to beams containing 10% of S.F addition. The cement content for concrete mixes was 500 Kg/m^3. All specimens were tested at 28 days to study the effect of bone powder (B.P) content on the hardened properties of compressive strength and tensile strength of concrete. The water-cement ratio (W/C) was 0.4 in all concrete mixes. In this study, four concrete mixes were made incorporating bone powder and silica fume [(0%), (5% bone powder), (5% bone powder and 5% silica fume), and (10% silica fume)]

Results showed that concrete mixes could be successfully developed by incorporating bone powder in the mix. The mechanical properties of concrete mixes containing 5% bone powder and 5% silica fume were higher to those containing 10% SF powder. The compressive and tensile strengths of concrete mixes containing 5% of bone powder and 5 % silica fume showed higher performance compared to other mixes. It was also observed that the fracture toughness of concrete mixes containing 5% bone powder and 5% silica fume increases as compared to other mixes. In addition, the fracture toughness based on Linear-elastic fracture mechanics (LEFM) and energy concepts for all mixes was found to decrease with increasing crack -depth ratio (a/w).

KEW WORDS: Silica fume, Bone powder, Compressive strength, Tensile strength, Fracture toughness.

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INTRODUCTION

Recent references have pointed to opportunities for the development of adhesives and sound or thermal insulation from meat and bone meal [1, 2]. The use of meat and bone meal for the production of porous clay bricks is reported from Germany [3]. The fats and proteins research foundation (FPRF) is initiating a project to explore the application of meat and bone meal in composite structures, such as concrete and asphalt materials and insulation for heat and sound.

For public health reasons, meat and bone meal can no longer be used as animal feed. A 1997 study conducted by France's public environmental agency ADEME concluded that the meal is destroyed in the 2000°C flame of a cement kiln with no detrimental impact on the environment or public health. Moreover, using the meat and bone meal in the cement plant's as a substitute for fossil fuels has cut CO_2 emissions and saved fossil energy resources, while providing an effective disposal solution for meat and bone meal. The use of meat and bone meal as animal feed is now prohibited in Japan, and an effective disposal solution had to be found. The combustion conditions of cement mill clinker kilns (temperature of 1450°C and long residence times) are suitable for the destruction of meat and bone meal under optimal safety conditions. Moreover, the meat and bone meal constitutes a significant source of energy, which can be tapped by using it as a substitute fuel.

Since the TSB crisis, Europe has had to increase its capacity to eliminate MBM and incineration has been a major method adopted by many countries. Bone meal is a mixture of crushed and coarsely ground bones that is used as an organic fertilizer for plants and in animal feed. As a fertilizer, bone meal is primarily used as a source of phosphorus. Bone meal is used as a supplement for calcium and phosphorus. It is composed of finely crushed, processed bone, usually from cattle but sometimes also from horses. Bone marrow may also be added to the product. Calcium in bone meal occurs as a calcium phosphate compound known as hydroxyapatite or hydroxylapatite. Hydroxyapatite is an inorganic compound found in the matrix of bone and the teeth; it confers rigidity to these structures. The formula of hydroxyapatite is $(Ca_3(PO_4)_2)_3{\cdot}Ca(OH)_2$ or $Ca_{10}(PO4)_6(OH)_2$ [4].

Meat and bone meal (MBM) is a by-product of the food industry, obtained by the removal of fat from mammal carcasses by a process of crushing, cooking and grinding. In Europe, more than 3 M tons of MBM are produced annually [5]. Before May 1st 2003, MBM were classified in Europe [6] according to whether they came from sources defined as high risk or low risk. The high-risk source concerned principally the MBM obtained from animals infected by transmissible spongiform encephalopathy (TSE), animals that had died of natural or unknown causes, and specified risk materials (SRM) such as brains, eyes, tonsils and spinal cords of bovine, ovine and caprine animals [7].

Linear-elastic fracture mechanics technology is based on an analytical procedure that relates the stress-field magnitude and distribution in the vicinity of a crack tip to the nominal stress applied to the structure, to the size, shape, and orientation of the crack or crack-like discontinuity, and to the material properties [8,9]. It is a well-established fact that a failure of concrete under load takes place through progressive internal cracking when the continuous crack pattern is extensively developed, thus resulting in decreasing the carrying capacity of concrete. The matrix parameters and the relative amounts of the concrete constituents largely affect the fracture toughness of concrete [10, 11, 12, and 13].

Silica-fume is a very fine pozzolanic material, composed mostly of amorphous silica produced by electric arc-furnace as a byproduct of production of elemental silicon or ferro-silicon alloys (also known as condensed silica-fume and micro-silica) (ASTM C1240-97) [14]. Silica-fume is added to concrete in a dry powder from a finally divider mineral admixture. The pozzolanic effect of silica-fume may due to its high silicon dioxide (SiO_2) content. SiO_2 reacts with the free lime $Ca(OH)_2$ (CH) which results from the hydration of cement in the presence of moisture, an additional (secondary) calcium silicates hydrate (CSH) is formed. This CSH is denser, homogenous and less porous, i.e. it has better physical properties than that result from the hydration of cement. The fineness of silica fume greatly enhanced the properties of concrete. This is because its extremely small particle size accelerates the chemical reaction and bridges the gabs between cement particles, so the structure becomes denser and less porous [15, 16, and 17].

In this study, an experimental investigation was carried out to study the use of bone powder as addition of cement on the fracture toughness of concrete beams. All beams containing bone powder were compared to beams containing 10% of S.F addition.

EXPERIMENTAL PROGRAMMED

Materials and Mix Proportions

Bone crusher was a device for crushing animal bones. Bones obtained during slaughter were cleaned, boiled in water and dried for several months to removal any organic materials. After that, they were suitable for crushing with the special machine into a relatively dry gritty powder.

The cement used in this study was type I ordinary Portland cement (OPC) according to E.S. 373/199. The cement content in the concrete mixes was 500 kg/m^3. The mineral admixtures used were silica fume and bone powder with specific gravities of 2.1 and 1.85, respectively. Tables 1 and 2 show the chemical composition of OPC, silica fume and bone powder. Natural fine clean sand free from impurities such as silt, clay and organic compounds were used as fine aggregate. Crushed dolomite with nominal maximum size of 14 mm was used as coarse aggregate. Tap water was used for mixing and curing works. Table 3 shows the physical properties for crushed dolomite, sand and bone powder. The water cementitious ratio was kept constant as 0.4. The dry constituents (cement, silica fume, bone powder, sand and dolomite) were mixed together for at least 60 seconds before the water and the admixtures have been added. The mixing time after adding water was at least four minutes. Four concrete mixes were made incorporating bone powder and silica fume [M_I (0 %), M_{II} (5 % bone powder), M_{III} (5 % bone powder and 5 % silica fume), and M_{IV} (10 % silica fume)]. High range water reducing admixture was (HRWR) was added with dosage of 2% by weight of cement content for concrete mixes to overcome the loss of workability due to the addition of bone powder and silica fume.

Experimental Procedures

ACI committee was used to determine the required quantities of materials for the test mix. Proportions adopted in this work were gravel: sand: cement: water/cement (1790: 895: 500 kg/m^3: 0.4). About 24 specimens (standard dimensions) were cast and tested at 28 days to study the effect of bone powder and silica fume addition on the compressive strength and indirect tensile strength of concrete. About 48 beams (10×10×35 cm) with different crack-depth ratios (a/w = 0.0, 0.2, 0.3, and 0.4) were caste and tested to study the effect of four concrete mixes on the fracture behavior of concrete. The notch at the tensile surface of the specimen was created by using a steel plate of 0.8 mm. Layouts of the experimental program are listed in Table 4. The molds were greased and prepared for casting. Concrete mixes were placed in three layers in the molds and then compacted by using electrical vibrating table for 30 seconds. The specimens were removed from molds after 24 hrs., marked and then immersed in curing medium. All beams were tested under 3-P configuration. Linear variable displacement transducer (L.V.D.T.) was used for measuring the mid span vertical deflection in notched plain concrete beam specimens. A universal hydraulic testing machine of capacity 1000 kN was used to test all specimens.

RESULTS AND DISCUSSIONS

Slump Test

The slump test was performed on the four mixes under investigation to measure their workability. The results of the test for the four mixes are given in Table 5. The table shows that the slump tests for mixes containing 5% bone powder and 5% silica fume (M_{III}) is higher than the flowability for the three mixes M_I, M_{II}, and M_{IV}. This may be attributed to the fact that the flowability of the mix increased by increasing the powder content.

Compressive Strength

The effect addition of bone powder and silica fume [M_I (0%), M_{II} (5% bone powder), M_{III} (5% bone powder and 5% silica fume), and M_{IV} (10% silica fume)] on compressive strength for concrete were shown in Fig 1. The figure demonstrated that the values of compressive strength of concrete at M_{II}, M_{III} and M_{IV} are higher than the compressive strength of control specimen concrete (M_I). The compressive strength ratio is the ratio between compressive strength of the concrete with bone powder (σ_c) to that of normal concrete (σ_{c0}). It can clear that the compressive strength ratio (σ_c/σ_{c0}) increases at M_{II} (5% B.P.), M_{III} (5% B.P. + 5% S.F.) and M_{IV} (10% S.F.) by a value of 16.6%, 20.1% and 13.2% respectively as shown in Fig. 2. The mix M_{III} which containing (5% B.P. + 5% S.F.) gives higher values of compressive strength when compared to mixes M_I, M_{II} and M_{IV}. This improvement in strength may be due to the setting of calcium phosphate cement is essentially a dissolution precipitation reaction, it is controlled by the particle size of the reactants: finer particles will dissolve faster than the coarse ones. The initial porosity is less in the mix containing bone powder, and the setting reaction operates on a shorter length scale. The resulting mix is denser with fewer and smaller pores and thus stronger.

Indirect Tensile Strength

The effect addition of bone powder and silica fume [M_I (0%), M_{II} (5% bone powder), M_{III} (5% bone powder and 5% silica fume), and M_{IV} (10% silica fume)] on tensile strength for concrete were shown in Fig 3. The figure demonstrated that the values of tensile strength of concrete at M_{II}, M_{III} and M_{IV} are higher than the tensile strength of control specimen concrete (M_I). The effect of four mixes on the indirect tensile strength ratio (σ_t/σ_{t0}) of concrete were shown in Fig. 4, the indirect tensile strength ratio is the ratio between indirect tensile strength of concrete with bone powder (σ_t) to that of normal concrete (σ_{t0}). It can clear that the tensile strength ratio (σ_t/σ_{t0}) increases at M_{II} (5 % B.P.), M_{III} (5% B.P. + 5% S.F.) and M_{IV} (10% S.F.) by a value of 20%, 23.3% and 17% respectively. Table 6 shows ($\sigma_t/\sigma c$), it is clear that the indirect tensile strength (σ_t) represents about 6.9%, 7.13%, 7.12% and 7.14% of its compressive strength (σ_c) at control specimen concrete (M_I), M_{II}, M_{III} and M_{IV}

respectively. This may be attributed to the fact that the calcium phosphate bone cements offer a route of obtaining orthocalcium phosphates in a monolithic form at physiological conditions, without sintering process, by means of a cementitious reaction. The calcium and phosphate precipitate within the mixture to form crystallites.

Fracture Behavior

The crack path through composite materials such as concrete depends on the mechanical interaction of inclusions with the cement-based matrix. Fracture energy depends on the deviations of a real crack from an idealized crack plane. The load-deflection curves and the load- crack mouth opening displacements (CMOD) illustrate the behavior of the fracture toughness of specimens.

Figures (5a, b, c and d) show the average of load-deflection of the un-notched beams compared to the average of load-deflection of the notched beams for the three points bending tests for all studied concrete mixes. The figures indicate that the fracture load-deflection were linearly up to failure for both un-notched and notched beams. On the other hand, mix (M_{III}) which containing (5% B.P. + 5% S.F.) recoded higher values of fracture load compared to mixes M_I, M_{II} and M_{IV}. Figures (6a, b, c and d) give the relation between load and crack mouth opening displacement (CMOD) for all concrete beam specimens in a similar manner to the load-deflection diagrams as mention above. It was noticed that the same trends of results for the load-deflection diagrams were observed as for the load-CMOD diagrams.

The fracture toughness (K_{IC}) based on linear elastic fracture mechanics (LEFM) for single edge crack specimen loaded in 3-P bending was calculated using ASTM standard E399 expression:

$$K_{IC} = [\frac{6\,M\sqrt{a}}{Bw^2}]Y(a/w)$$

$$Y(a/w) = 1.99 - 2.47(a/w) + 12.97(a/w)^2 - 23.17(a/w)^3 + 24.8(a/w)^4$$

Where- :

a = Initial notch depth

w = Specimen depth (100 mms)

M = Bending moment = $P_c \times L/4$

P_c = Applied load at crack initiation

L = Loaded span (300 mms)

B = Specimen width (100 mms)

The fracture toughness, K_{IC}, against a/w for all studied concrete mixes was illustrated in Figure 7. It is clear to note that K_{IC} decreased with increasing a/w for all concrete mixes. This is a typical behavior of concrete materials [18]. On the other hand, mix (M_{III}) which containing (5% B.P. + 5% S.F.) recoded higher K_{IC} values compared to mixes M_I, M_{II} and M_{IV}. This is because of higher values of cracking load (P_c) thus increasing values of (K_{IC}) where: K_{IC} = Constant × P_c. Under addition 5% B.P. + 5% S.F. (M_{III}), the load displacement behavior and fracture toughness can be improved. For example, the fracture toughness for mix (M_{III}) was over 1.1, 1.31 and 1.53 times that of concrete M_{II}, M_{IV} and M_I respectively. This can be attributed that the mix (M_{III}) are able to transfer emerging loads by bridging the cracks. This may be attributed to the enhancement in the bond between matrix and coarse aggregates and therefore a decrease of in microscopic crack growth with high loading.

The cracks initiated and propagated in the same direction and plane regardless the depth of the pre-notch. Based on this fact, the strain energy release rate, G, is suggested to be calculated by subtracting the energies absorbed by the two beams had different a/w and then divided by the difference between the un-cracked area in each beam, i.e. G is calculated in each interval (a/w = 0.0-0.2, 0.2-0.3, and 0.3-0.4). Therefore, the mean values from load–deflection curves for four mixes and different a/w were drawn and the area under these curves was calculated as the energy absorbed up to complete failure see Table 7.

It is clear that, there is a wide discrepancy between the values of G in each material for the range "0.0-0.2". As known, the fracture toughness can be expressed by G, $K_{IC} = \sqrt{GE}$. According to the Egyptian code of practice, the modulus of elasticity $E = 4400\sqrt{\sigma_{cu}}$ MPa, where σ_{cu} is the 28 days cube compressive strength. Therefore, the mean value of K_{IC} is calculated in each material based on the mean values of G excluding the values of the range "0.0-0.2", as shown in the Table 7.

Based on Hillerborg concept, i.e. total energy, [19], the K_{IC} for different notched plain concrete beams was calculated from the relation $K_{IC} = \sqrt{GE}$. The fracture toughness based on Hillerborg concept against a/w for various studied mixes was illustrated respectively in Figure 8. The figure shows similar behavior as that for K_{IC} (LEFM) shown in Figure 7. The fracture toughness based on Hillerborg concept of mix (M_{III}) is higher than that of mixes M_I, M_{II} and M_{IV}. The average values for K_{IC} based on Hillerborg concept are listed in Table 8. The K_{IC}, which is calculated based on the LEFM and the suggested subtracted energies for different all mixes are present in this Table. The K_{IC}, which is calculated from Hillerborg model, shows similar trend to that calculated from LEFM. However, the K_{IC} value, which is calculated, based on subtracted energies method are much higher than those calculated from the other two methods.

CONCLUSIONS

Based on the test results from this study the following conclusions could be drawn as follows:

1- Mixes containing 5% bone powder and 5% silica fume (M_{III}) can give an excellent deformability than the three mixes M_I, M_{II}, and M_{IV}.
2- The deflections of the beams containing (5% B.P. + 5% S.F.) tested in flexure was generally higher to those of the reference beams.
3- The mix M_{III} which containing (5% B.P. + 5% S.F.) gives higher values of compressive and tensile strengths when compared to mixes M_I, M_{II} and M_{IV}.
4- The fracture toughness increases for concrete mixes containing (5% B.P. + 5% S.F.) when compared to mixes M_I, M_{II} and M_{IV}
5- The fracture toughness for all studied concrete mixes decreased with increasing crack-depth ratio (a/w).
6- The values of K_{IC} calculated based on LEFM or energy concept were found to be reasonable.

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Table 1: Chemical Composition of OPC and silica fume.

Oxides	Chemical Composition (wt%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
OPC	20.39	5.05	2.89	62.00	2.07	2.40	3.10
Silica fume	96.4	0.77	1.05	0.07	0.03	0.58	-

Table 2: Chemical composition of bone powder.

CaO	P_2O_5	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	LOI
52.45	36.85	1.34	0.35	0.25	1.3	1.6	0.3	0.41	1.2

Table 3: physical properties for crushed dolomite, sand and bone powder

Description	Dolomite	sand	bone powder
Specific gravity	2.45	2.57	1.85
unit weight (t/m^3)	1.48	1.79	0.690
Absorption, %	1.4 %	0.42	11
Impact value(I.V.), %	17.5 %	-	-
Fineness modulus	6.9	2.49	0.07

Table 4: Layout of Used Mixes.

Mix code	Type of test						No of specimens		
	Compression	Tensile	Fracture test				Cubes 7×7×7 (cm)	Cylinder 7.5×15 (cm)	Beams 10×10×35 (cm)
			a/w = 0.0	a/w = 0.2	a/w = 0.3	a/w = 0.4			
M_I			-	-	-	-	3	3	-
M_{II}			-	-	-	-	3	3	-
M_{III}			-	-	-	-	3	3	-
M_{IV}			-	-	-	-	3	3	-
M_I							-	-	3
M_I							-	-	3
M_I							-	-	3
M_I							-	-	3
M_{II}							-	-	3
M_{II}							-	-	3
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M_{II}							-	-	3
M_{III}							-	-	3
M_{III}							-	-	3
M_{III}							-	-	3
M_{III}							-	-	3
M_{IV}							-	-	3
M_{IV}							-	-	3
M_{IV}							-	-	3
M_{IV}								-	3

Table 5: results of slump test for concrete mixes.

Mix design	Mix (I)	Mix (II)	Mix (III)	Mix (IV)
Slump value (mm)	200	70	75	85
Types of slump	Collapse slump	True slump		

Table 6: Test results of average $\sigma_t/\sigma_{c\%}$ for concrete.

Mix code	Bone powder (B.P.),%, Silica fume (S.F.),%	compressive strength (σ_c) (Mpa)	tensile strength (σ_t) (Mpa)	$\sigma_t/\sigma_{c\%}$
M_I	0	43.3	3	6.9
M_{II}	5% B.P.	50.5	3.6	7.13
M_{III}	5% B.P.+ 5% S.F.	52	3.7	7.12
M_{IV}	10% S.F.	49	3.5	7.14

Table 7: Strain energy release rate, G, and K_{IC} for all mixes.

Mix code	a/w			Mean	
	0-0.2	0.2-0.3	0.3-0.4	G, N/mm	K_{IC}, MPa.mm$^{0.5}$
M_I	.094	0.131	0.063	0.097	52.18
M_{II}	0.149	0.21	0.115	0.163	70.5
M_{III}	0.206	0.293	0.165	0.229	84.3
M_{IV}	0.12	0.169	0.0968	0.133	63.3

Table 8: Average fracture toughness based on LEFM and energy methods.

Mix code	K_{IC}(subtracted energies) MPa. mm$^{0.5}$	K_{IC} (LEFM) MPa. mm$^{0.5}$	K_{IC}(Hillerborg) MPa. mm$^{0.5}$
M_I	52.18	22.1	18.64
M_{II}	70.5	29.5	25.5
M_{III}	84.3	31.9	31.9
M_{IV}	63.3	25	22

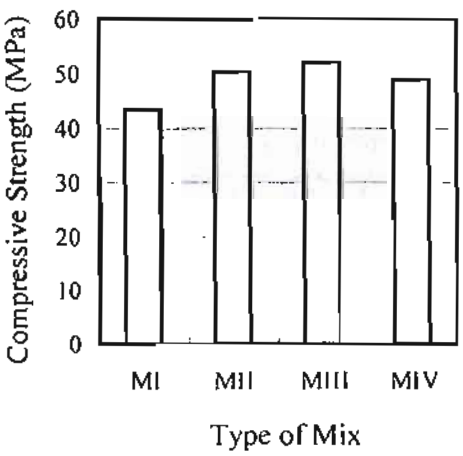

Fig. 1. Compressive Strength vs Type of Mixes.

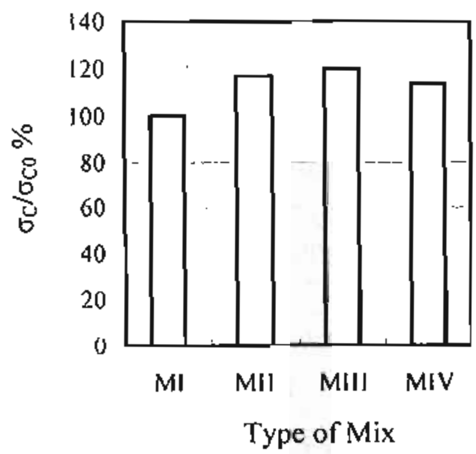

Fig. 2. Relative Compressive Strength vs Type of Mixes.

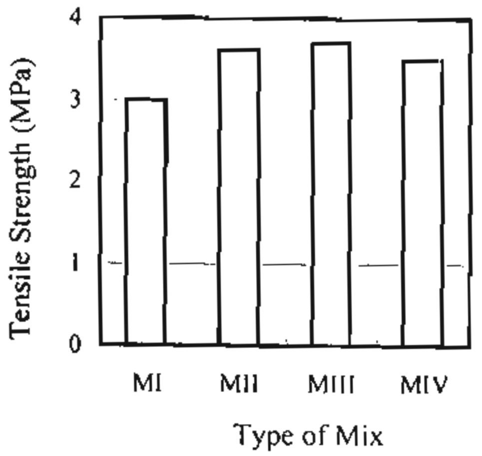

Fig. 3. Tensile Strength vs Type of Mixes.

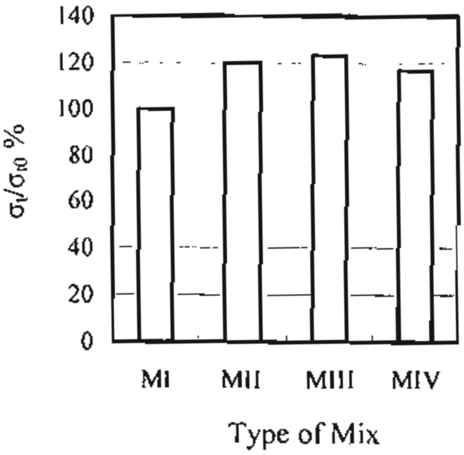

Fig. 4. Relative Tensile Strength vs Type of Mixes.

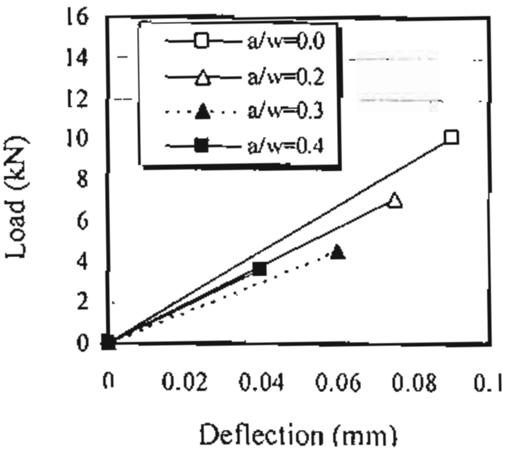

Fig. (5-a): Load vs Deflection for M_I and different a/w.

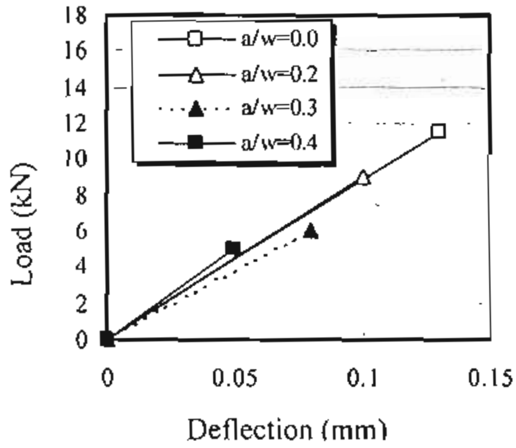

Fig. (5-b): Load vs Deflection for M_{II} and different a/w.

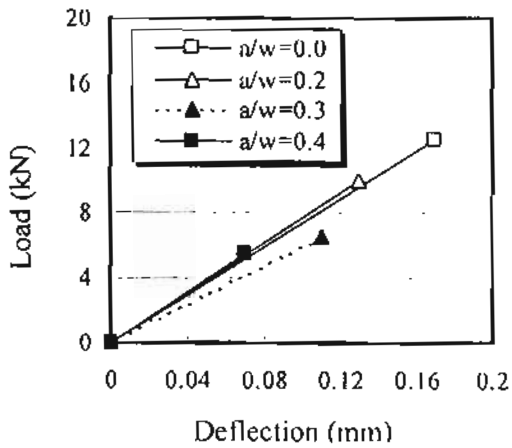

Fig. (5-c): Load vs Deflection for M_{III} and different a/w.

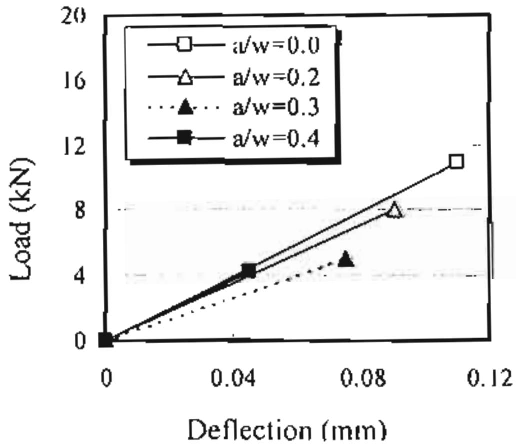

Fig. (5-d): Load vs Deflection for M_{IV} and different a/w.

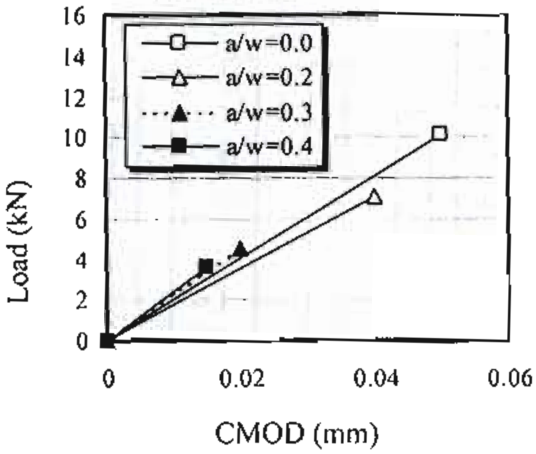

Fig. (6-a): Load vs CMOD for M_I and different a/w.

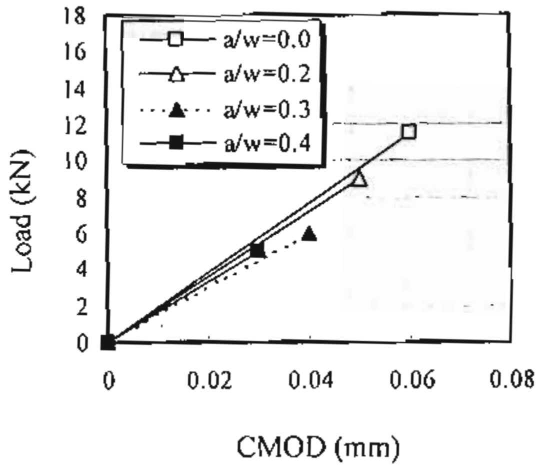

Fig. (6-b): Load vs CMOD for M_{II} and different a/w.

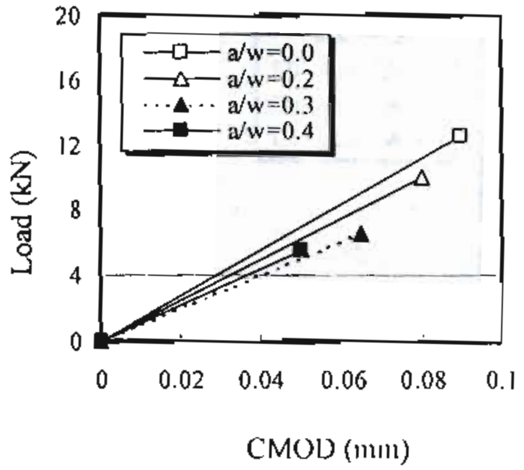

Fig. (6-c): Load vs CMOD for M_{III} and different a/w.

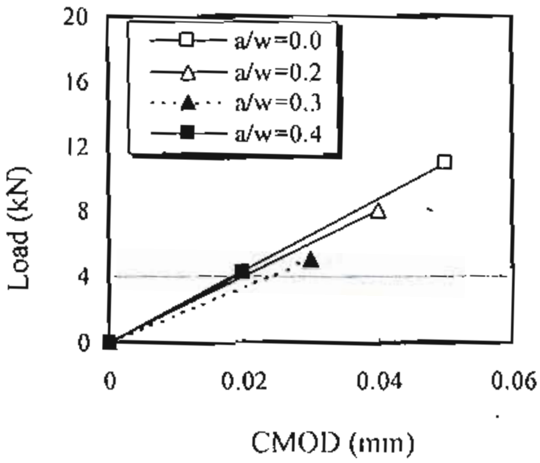

Fig. (6-d): Load vs CMOD for M_{IV} and different a/w.

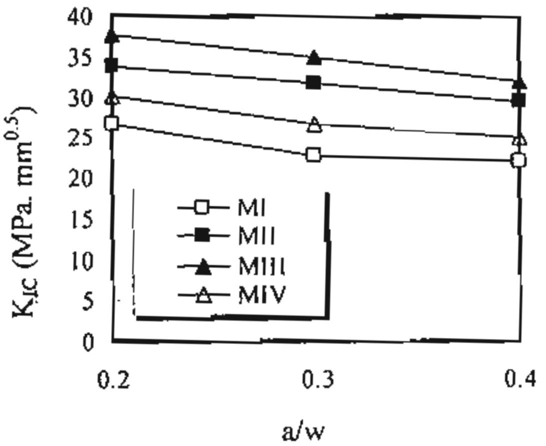

Fig. 7. Variation of K_{IC} Based on LEFM Concept with a/w.

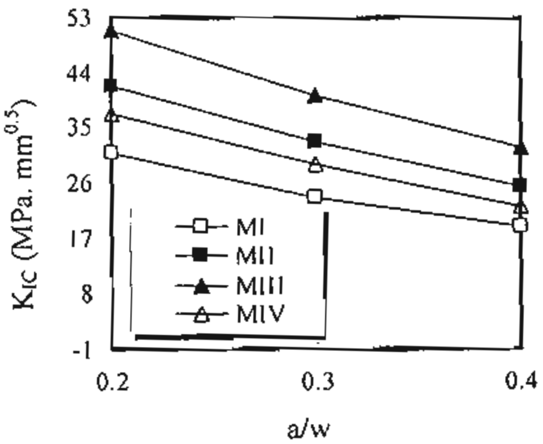

Fig. 8. Variation of K_{IC} Based on Hillerborg Concept with a/w.