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CONTROL OF SHRINKAGE CRACKING IN END RESTRAINED REINFORCED CONCRETE WALLS

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ABSTRACT

Through this study, it has been endeavored to find out the final cracking pattern of shrinkage cracking in the walls of base and ends restraint and with different (L/H) ratios to predict the suitable position of horizontal reinforcement to be effective as a means of limiting the width of cracks due to restrained shrinkage. In this study reduced scale of reinforced mortar walls were used. Many characteristics of reinforced walls were measured such as restrained wall movements, crack spacing, crack width, crack lengths, drying conditions, different length to height ratios and their relationships after an exposure period of drying shrinkage. These walls were exposed to drying shrinkage through a period of three months in Winter and two months in Summer.

It has been found that the number of cracks increased with increasing the length/height ratio also the number of cracks for all walls of different (L/H) ratios were greater than that restrained at the base only in previous researches, this is due to presence of end restraint. All cracks that formed in walls of (L/H)=(2) were secondary cracks (crack height less than wall height), while the cracks that formed in walls of (L/H) more than (2) were secondary and primary cracks (crack height reach to the full wall height). Crack spacing increased with increasing wall height. Cracking height increased with increasing length to height ratio. Height of cracks in the walls of (L/H=2, 4, 8) ranged between (0.2-0.6)H, (0.3-0.8)H, (0.4-0.9)H respectively. The relationship between cracks spacing and wall height were: $S_{ave.}$=(0.92H, 0.96H, 0.88H) for (L/H=2, 4, 8) respectively.

The height of the maximum crack width decreases with increasing length to height ratio were:

$Y_{w.max}=0.62H_c$ for(L/H=2), and $Y_{w.max}=0.4H_c$ for (L/H≥4).

INTRODUCTION

The volume changes that considered in this study(***Abbas, 2009***) is that caused by changes in moisture content in the mortar body. This change results in the contraction of the volume. Shrinkage movement will not induce stresses in the concrete or mortar mass unless this member is restrained, the restrained movement will produce tensile stresses in the body, and may produce cracking if they exceed the tensile strength or strain capacity of the mortar itself.

Free movement of concrete members (unrestrained) is rarely present in practice, in which a rigidly interconnected parts are concreted at various stages. Thus the older sections restrict the newly concreted parts. Many researchers (**Kheder, 1986**, **Al Tamimi**, **1987**, **Al Mashhadi**, **1989**) studied the mechanism and control of shrinkage and thermal cracking in reinforced mortar and concrete walls. They were concerned with different types of cracks (primary and secondary cracks) in only base restrained walls. These cracks can occur in walls with length to height ratio greater and smaller than about 2.5, which is usually associated with low and high walls. The results of most concrete walls had been neglected due to the very poor results, therefore it has been depended on mortar walls in this study.

In high walls such as tunnels and other retaining structures, with wall heights greater than about 4 to 5m, the length of these walls is usually not longer than about (10-15m), the length to height ratio for these walls is less than 2.5, whereas in long retaining walls, aqueous reservoirs or long tunnels, the length to height ratio for these walls increased to be greater than 2.5. The long wall casted in sequenced parts for construction purposes. The previous parts joined with the next parts by horizontal steel reinforcements to create a case of single or two end restraint, so that after drying shrinkage commence, each part will be restrained at both sides by two adjacent panels and its base. ***Abbas, 2009*** has been tried to study this problem in this research with end and base restrained walls of different (L/H) ratios. To simulate this problem to practical site conditions, reduced scale of mortar walls were casted and they were exposed to the outdoor conditions.

TYPES OF SHRINKAGE

1. Autogenous shrinkage: ***Véronique Baroghel-Bouny'*** and ***Pierre Mounanga***, ***2005***, found through their experimental results that, at a given age, the magnitude of autogenous shrinkage increases linearly as W/C decreases from 0.60 down to 0.25 (an increase of 1025 µm/m has been recorded on the "ultimate", *i.e.* 1-year, value.

2. Plastic shrinkage: ***Gary Ong and Kyaw ,(2006)*** reported that When freshly-cast concrete is exposed to a dry environment, plastic shrinkage occurs which is associated with the deformations that arising from a difference in vapour pressure inside the fresh concrete.

3. Drying shrinkage: Drying shrinkage ranges from less than 200 millionths for low slump lean mixes with good quality aggregate and under high relative humidity environment to over 1000 millionths for rich mortars or some concretes containing poor quality aggregates and an excessive amount of water under low relative humidity environment ***(ACI committee 207)***.

4. Carbonation shrinkage: The carbonation shrinkage develops only in the layers of concrete exposed to air with relative humidity limits of 30 to 70%. Carbonation shrinkage is caused by the chemical reaction of hydration products with carbon gas from the air. Under the actions of drying and moistening the carbonation shrinkage is coupled with drying shrinkage and provokes very fine cracks. Effects of carbonation shrinkage are superficial ***(CEB-FIB, 2006).***

EXPERIMENTAL WORK

Three different shapes (length/height) mortar walls has been casted in Winter and another three mortar walls casted in Summer. Three shapes were of dimensions (2*1*0.1)m, (4*1*0.1)m, and (4*0.5*0.1)m, (length*height*thickness) respectively. The (L/H) ratios of these three shapes were (2,4,8) respectively has been chosen so that one of them less than 2.5 and the others, more than 2.5 to study the two types of cracks (secondary cracks in walls of (L/H) ratio less than 2.5 and primary cracks in walls of (L/H) more than 2.5).

To reduce the time interval that required to form a rigid lateral and base restraint of walls, a rectangular steel frame were constructed of W-shape steel beams with a base of semi natural roughness performed by welding a (4) deformed bars φ (10)mm along the top surface of the (I) section to simulate the natural roughness of the base

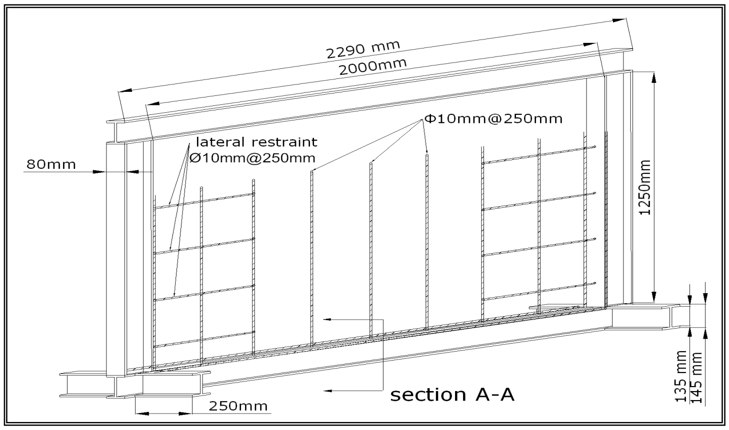
Edge and base restraint of walls

The restraint of the walls were conducted by construction a rectangular steel frames. The properties of the steel beams that used were W-shape of cross sectional area of (1758)mm^2, web height (145)mm, and flange width (80)mm. The frames were checked structurally for the restraining purposes. Each frame were composing of lateral two steel column (end restraint), lower steel beam (base restraint), and the upper steel beam, were fixed the all parts to each other at ends by welding to form a monolithic single frame as shown in Figure (1).The vertical and lateral dowels were fixed to frame by welding to give the efficient restraint. To increase the roughness of the base, (4) steel deformed bars φ (10)mm has been welded along the upper surface of the base as shown in Figure (2).

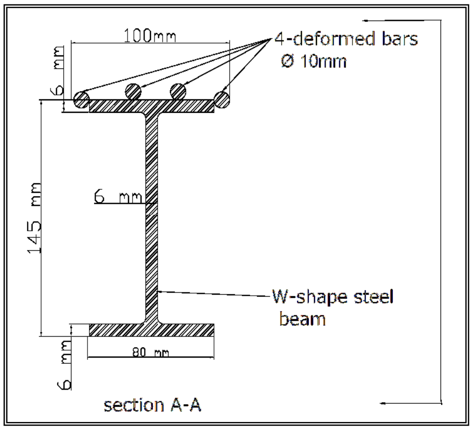
The chosen of this type of restraint was for two reasons, firstly to reduce the time required to exhaust the shrinkage strain of the base which might extend for several months. secondly, the thermal expansion of steel is similar to that of concrete as reported by ***ACI committee 207*** and ***209***.

Molds of the Walls

The form work that used in the casting of the walls composed of four ply woods of dimension (1*2.4)m and thickness (0.016)m and two steel plates of (2*1)m with thickness of (0.9)mm, were fixed on the internal face of the frontal 2-ply woods to give a good surface. The surfaces of the steel plates were greased with oil before using to facilitate the dismantling of the molds. The ply woods of both sides were supported by timber joists of length (1.5)m and cross sectional area of (0.05*0.1)m on each sides with spacing of (0.5)m.



Figure(1) Edge and base restraining steel frame of (Length/Height)ratio equal(2)



Figure(2) cross section of the restraining steel base of three different (Length/Height) mortar walls

Materials:

Deformed steel bars of 10 mm diameter were used. The average yield strength of three samples is 425 MPa**.** The cement used in this study was ordinary Portland cement manufactured by the New Cement Plant of Kufa. This cement complied with the ***Iraqi specification(I.O.S.) No.5/1984.*** The fine aggregate that used of fineness modulus was (2.64) and complied with the ***Iraqi specification*** 45:1984 Limits Zone (2)

Mortar mixes:

All sets of walls were casted with a single mortar mix. The mix proportion was (1:2) (cement : sand) by weight and effective w/c ratio of (0.5).

Mixing procedure and castig:

Mixing procedure is important to obtain the required homogeneity of the mortar mix. The mixes were placed in the molds in four lifts, each lift was compacted internally by using electrical vibrator. The sequence of mixing steps are shown in table (1).

Table(1) Steps of mortar mixing

sand + 1/2 of water	Mixing 1 minute
1/2 of cement	Mixing 1 minute
1/2 of cement	Mixing 1 minute
1/2 of water gradually	Mixing 2 minute

Curing and exposure:

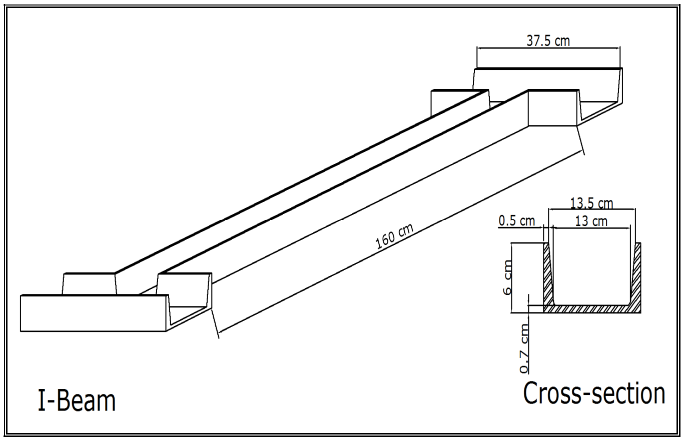
To prevent plastic shrinkage cracking due to rapid evaporation from the upper surface of the walls and beams of elastic tensile strain and free shrinkage cured according ***ASTM C192***, polythene sheets were used to cover the upper surface of the beams and walls after the casting. The walls and beams were cured by covering them with wetted Hessian and polythene sheets and wetted once every day for first 7-days, then air dried in uncontrolled laboratory and outdoor conditions until age of 60-days.

Testing of Specimens:

For each set of walls, (12) cubes of (100)mm for compressive, (12) cylinders of (100*200)mm for splitting, and (12) cylinders of (150*300)mm for modulus of elasticity were casted for two age. The compressive strength of (7) and (28) days were (24)Mpa and (30)Mpa, whereas the (7) and (28) days splitting tensile strength were (5.31) and (6.46)Mpa, and the modulus of elasticity of (7) and (28) days were (36)Gpa and (40)Gpa respectively.

Elastic tensile strain capacity tests:

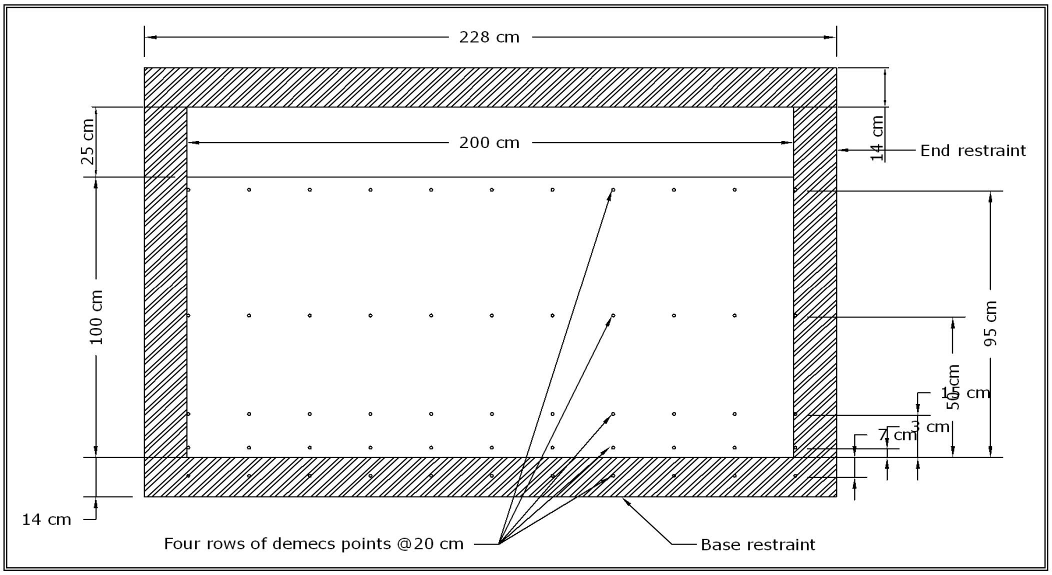
Elastic tensile strain capacity of mortar measured according to the direct method by using the same I-shaped steel mold (Al-Rawi, 1985) as shown in the Figure (3). Plain mortar beam were casted and allowed to shrink. Soon after the first crack occurred, the amount of strain which was relieved as a result of elastic recovery of restrained mortar, crack width was measured by microscope divided by the total length which was assumed to represent elastic tensile stain capacity of mortar.



Figure(3) Steel I-Beam mold for elastic tensile strain and free shrinkage measurement

Free volume change:

In order to measure the full free volume change of the mortar walls, beam of plain mortar were cast in the same I-shaped mold of Figure (3) with an artificial crack (gap) was made in the mid-span of the beam by using a (4) mm plastic diaphragm , and exposed to the same conditions of restrained mortar walls . The friction in the contact surfaces between the mortar and the mold was minimized by applying two layers of greased polythene sheets, , and covered with polythene sheet after casting of the beam to avoid the rapid plastic shrinkage and cured daily for (7)days and then subjected to exposure conditions similar to those of the walls . this beam was left free to shrink and move. The movements were measured by two demec points were fixed adjacent the gap sides and an extensometer. The measuring were continued for the same period of walls measurement (about 60 days) to represent free volume change with time .Surface strain measurements of the walls and of the restraining base were carried out by using 4 rows of demec points fixed on the walls and one row fixed on the steel base as shown in Figure(4).



Figure(4) Fixing of demecs on wall(2*1)m

Wall notation:

All sets of mortar walls were of mix proportions (1:2:0.5), (cement, sand, w/c ratio) respectively. Table (2) shows the walls shapes and notation for both sets of Summer and Winter.

Table (2) Wall characteristics

Wall notation	Wall dimension (length*height)m	Time of casting	Mix proportion Cement:sand:w/c	P% (Horizontal)
2W	2*1	Winter (January)	1 : 2 : 0.5	0.3
4W	4*1			
8W	4*0.5			
2S	2*1	Summer (June)	1 : 2 : 0.5	0.3
4S	4*1			
8S	4*0.5			

The measurements of temperature and relative humidity are shown in table (3).

Table (3) average temperature and relative humidity

Month	Temperature (av.) c°	Relative humidity %
February	27	44
March	30	48
April	35.5	36
May	36.5	31
June	39.5	26
July	48	28
August	45.5	31
September	41.8	35

Crack widths were measured for each (10)cm of crack height from the base .The measurements were carried out by using a portable measuring microscope with 40X magnification and a measuring field of 3.5mm.

Plate(1) wall (4w)

Plate(2) wall (8W)

Plate(3) walls (2S, 4S, 8S)

RESULTS AND DISCUSSION

Free volume change:

The first measurement for this model were taken after (7)days of casting immediately after curing period to avoid more losses of shrinkage strain. Figure (5) shows the free shrinkage of I-shape mortar model. The maximum value of free shrinkage of I-shape beam that obtained in this work were (1235) microstrain through a period of (45) days.

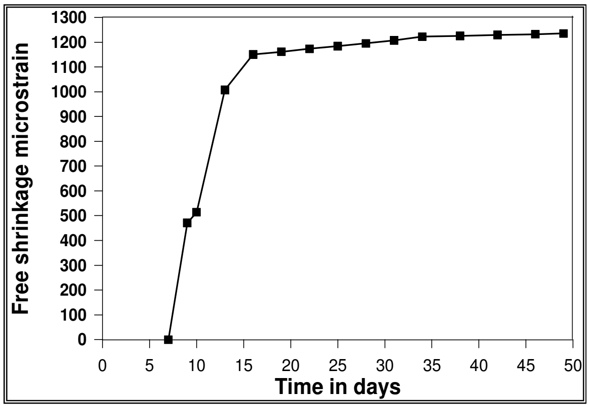


Figure (5) Free shrinkage strain of I-shape plain mortar

Elastic tensile strain capacity:

Elastic tensile strain capacity of mortar was obtained by measuring the crack width by crackmeter immediately after cracking of I-shape plain mortar beam and divided by the total restrained length of the beam. This beam cured for (7) days and then exposed to the same outdoor conditions of walls. The value of (ε_{ult}) of mortar is (175) microstrain. It was obtained after (12) days of casting where the first crack initiation.

Restrained Wall Movement:

The horizontal wall movements during the observation period were measured at four different levels (3,15,50 and 95 cm above the base) by using extensometer to investigate the effect of base and end restraint with different Length/Height ratios on the final cracking pattern. The strains of each row for all walls in Winter and Summer were measured and drawn. Figures (6) shows the strains of wall (8w) at height (45) cm.

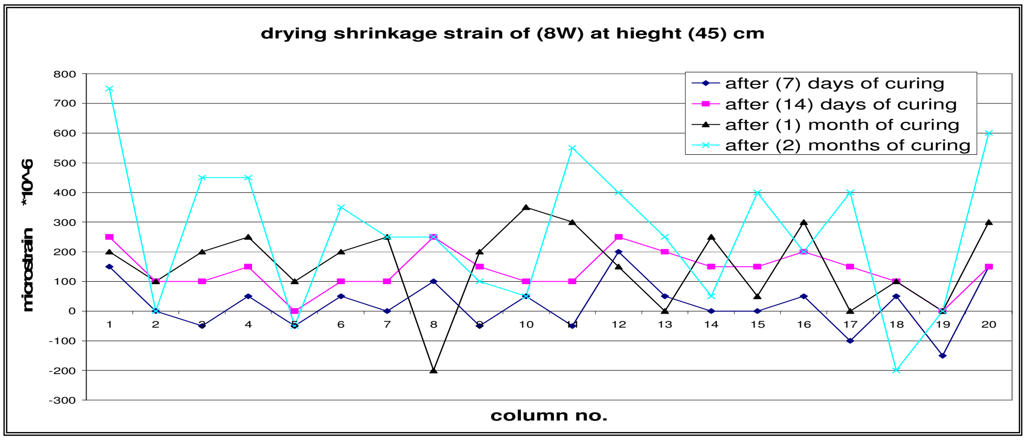


Figure (6) drying shrinkage strain of wall (8W) at height (45) cm

Through the observations of these measurements of each row in all walls, it has been found the following:

1. Most of the absolute positive values is greater than the absolute negative values, this means that the amount of total drying shrinkage of each row is greater than the total amount of expansion and this means the end restraint has a partial effect on the members of end restraint.
2. The absolute positive and negative values for each wall, decreased toward the base, this means that the effect of base restraint appeared gradually toward the base to reduce the induced strains of end restraint.
3. The summation of all strains (positive and negative) of each row produces positive value, this means that the walls tend to shrink, although the end restraint, this refer to a slippage were occurred in the end restraint or loss of restraint in steel frame.
4. The amount of drying shrinkage strain of each wall in Summer is greater than in Winter for the same wall shape.
5. The negative values of strains represent there is an expansion in this column and the repeated negative values in the same position represent initiation a crack in this column.
6. The amount of slippage after cracking was less than that obtained in the previous researches due to the presence of end restraint as well as the high base restraint where the restraining surface of base per unit length is equal to wall thickness plus perimeter of four welded bars on the base whereas in the previous researches the restraining surface per unit length is equal to wall thickness only.
7. Most final measurements of strains near the ends prone to abrupt high positive value, this represent occurrence of slippage in the end restraint.
8. The final strains of shrinkage and expansion in Summer for each wall approximately equal or larger with small percent than that in Winter, this means the high rate of drying shrinkage in summer the main effect responsible for cracking.

The contraction of the base during the exposure period of the wall was called loss of restraint (L_r). The difference in the measured contraction between the base and the wall at their contact surface before the occurrence of the cracking, represent the slippage between them (sl_b) whereas the difference in the measured strain between the base and the wall at their contact surface at the end of the exposure period represent the slippage after cracking (sl_a). The average (l_r, sl_b, sl_a) measured for all walls (8W, 4W, 2W, 8S,4S,2S) which are illustrated in table (4).

Table(4) Losses of base restraint, slippage before, and slippage after cracking in the contact surface

Set order	Wall notation	L_r $*10^{-6}$ (microstrain)	Sl_b $*10^{-6}$ (microstrain)	Sl_a $*10^{-6}$ (microstrain)
winter set	8W	62.5	0	107.5
	4W	57.5	75	65
	2W	41.5	8.5	9
Summer set	8S	70	30	40
	4S	75	32.5	67.5
	2S	35	0	15

Cracking of walls:

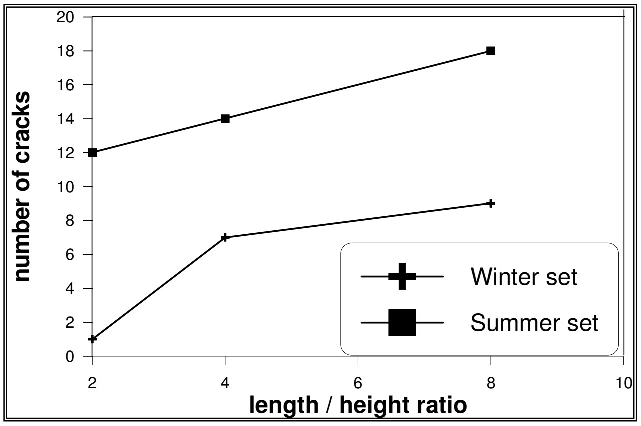


Figure (7) Relationship of number of cracks with different (L/H) ratios of walls in Winter and Summer

As shown in Table (5) and (6) and Figure (7), the effect of environment conditions (temperature and humidity) were very large on the drying shrinkage and cracking of walls, the number of cracks and the average crack, the first reason of these results was the presence of walls in moist environment in Winter reduces the drying shrinkage and then the mortar will have a slight increase in the tensile strength before drying onset whereas in Summer the mortar stressed before acquiring the sufficient hardening, so that the mortar can not withstand the cracking. The second reason was the creep of mortar in Winter can take its role to relief the induced stresses before cracking initiation (***Jae, 2006***, found that the specimen of mortar of fine aggregate volume (55%) does not reach the maximum tensile strength of (5)MGP, but cracked with stresses of (1.8)MGP due to drying shrinkage). Cracking height increase with the increasing of (L/H) ratio. These results, according to ***ACI committee 207, 1995,*** where the wall of base restrained, the degree of restraint increased upward with increasing of (L/H) ratio, therefore the height and number of cracks will increase consequently.

Table (5) cracking data of walls (Winter set)

1st set. (Winter)					
Wall name	Distance from left edge cm	Crack height cm	Maximum crack width mm	Height of max. crack width cm	Crack no.
2W	55	21	0.1	6	1
	150	15	0.05	5	2
4W	30	15-25	0.02	5	1
	95	45-60	0.03	5	2
	135	0-25	0.08	10	3
	175	0-45	0.3	35	4
	205	0-20	0.04	5	5
	295	0-30	0.08	10	6
	335	0-20	0.04	5	7
8W	145	5-23	0.04	8	1
	165	10-25	0.03	5	2
	200	0-15	0.02	5	3
	220	0-40	0.16	5	4
	245	0-30	0.08	10	5
	265	5-25	0.08	15	6
	320	0-15	0.02	5	7
	350	10-24	0.03	10	8
	385	0-23	0.03	8	9

Table (6) cracking data of walls, (Summer set)

2nd set. (Summer)					
Wall name	Distance from left edge cm	Crack height cm	Maximum crack width mm	Height of max. crack width cm	Crack no.
2S	25	0-36	0.08	21	2
	32	0-15	0.03	5	5
	48	10-48	0.04	20	3
	50	23-47	0.06	9	3
	60	5-19	0.03	10	3
	77	0-67	0.04	40	2
	99	5-60	0.03	40	2
	116	3-52	0.14	34	1
	126	0-45	0.1	20	2
	141	0-22	0.03	7	4
	165	5-45	0.2	25	3
	180	5-52	0.08	40	1
4S	40	0-50	0.06	20	5
	80	0-100	0.14	40	4
	133	0-32	0.2	12	2
	137	2-70	0.14	25	3
	148	0-52	0.06	7	2

	180	15-80	1.0	25	4
	185	0-100	1.0	50	1
	193	0-29	0.2	4	1
	216	3-30	0.02	12	2
	245	7-41	0.04	14	1
	264	5-45	0.04	10	2
	302	0-70	0.28	34	3
	333	20-60	0.04	20	3
	355	13-48	0.04	15	2
8S	29	5-32	0.04	5	3
	52	0-24	0.04	20	3
	72	5-27	0.04	7	3
	107	0-32	0.14	17	4
	156	0-47	0.10	17	2
	200	0-30	0.04	15	5
	210	11-43	0.04	17	3
	233	0-19	0.04	4	4
	259	0-32	0.04	17	4
	276	0-32	0.04	7	1
	287	0-47	0.14	17	4
	302	0-23	0.04	8	5
	320	5-37	0.04	7	4
	331	10-46	0.03	5	3
	337	0-32	0.08	7	5
	348	8-39	0.03	6	2
	364	0-45	0.15	10	3

Table (7) shows a comparison of cracks number with previous research. ***Abbas, 2009*** found that the number of cracks that induced in wall of (L/H=2) (2S) is greater than that had been found by ***Kheder, 1986*** and ***AL Mashhadi, 1989*** of only base restrained walls of (L/H=2). Also for walls of (L/H) greater than (2), it has been found the number of cracks in wall of (L/H=4) is greater than the number of cracks had been found by ***Kheder, 1986*** of wall of (L/H=5). This means the case of end restraint has a significant effect on the final cracking pattern of walls with different (L/H) ratio.

Table (7) comparison of minimum crack spacing with other researcher

Wall shape (L/H)ratio	Mix proportion	Ratio of steel reinforcement	No. of cracks	Min. crack spacing	researcher
2	1:2	0.4%	12	0.1H	Abbas kadhim
2	1:2	0.4%	4	0.28H	ALMashhadi
2.5	1:3	0.4%	2	0.8H	Kheder
4	1:2	0.4%	14	0.25H	Abbas Kadhim
5	1:3	0.4%	9	0.6H	Kheder

Cracking age and sequence:

Abbas, 2009 has been observed more than one of initial cracks were induced in the same time at different spacing of the wall length. In each intermediate spacing of initial cracks, an another group of cracks were formed. With progress of initial cracks age, these cracks will develop in length and width and another cracks will initiate. The crack initiation of most walls were in the lower third of wall height and then developed upward and downward.

The initiation of cracks of base and end restrained walls with (L/H) less than (4) were complied to the ***ACI committee 207, 1995*** in the cracking sequence of the continuous base restrained walls with few differences. The ***ACI committee 207, 1995*** states that the highest degree of restraint in the bottom of wall centerline, therefore the first crack induced in this position. After formation of first crack, the degree of restraint will decrease to zero and new distribution of restraint will form, the new highest degree of restraint in the centerline of new two halves of wall, therefore another cracks will form in this positions this can be seen clearly in walls of (L/H≤4) as shown in Figures (11) and (12).

In walls of (L/H=8) the cracks initiate in the upper third and then descend toward the base. After that new (L/H) will form, therefore the cracks will initiate in the lower third of wall to comply to the same effect of walls of (L/H≤4) that mentioned previously, as shown in the Figure (13), this attributed to the end restraint, where the upper part of the wall restrained in both ends only, therefore the total drying shrinkage of this line will induce small no of cracks with large cracking width, this will lead to quick formation of cracks, while the lower part of the wall restrained by end and base, therefore the total drying shrinkage of this line will induce a large number of cracks with very small cracking width (effect of base restraint) and this will lead to delay the formation of cracks after that of upper part of wall. All cracks that formed in three walls of Winter set were secondary cracks, while the cracks of Summer set were composed of two types of cracks, secondary cracks in wall of (L/H=2) and (secondary and primary) cracks in walls of (L/H=4,8) to confirm the theory of base restrained walls of ***ACI committee 207*** and the results of previous researches.

Due to the high rate of drying shrinkage in hot and dry weather (Summer) and consequently the development of the tensile stresses is greater than the development of tensile strength in the early ages, therefore the walls of (L/H) greater than (2) can produce primary cracks while the walls of Winter set of the same (L/H) can not produce that, this due to the creep effect which can take its role to relief the slowly induced stresses consequently the primary cracks can not form.

As shown in Figures (8) to (13) all cracks that formed along the wall length were vertically aligned in comparison with that of base restraint walls. This case of vertical cracking differ from the cracks that induced in the base restrained walls, where the cracks that formed near the ends splayed laterally. The reason of this difference were the effect of end restraint that let the wall of end and base restraint near the ends to behave as a continuous wall subjected to equal and opposite horizontal stresses that produce vertical cracking, while in the walls of base restraint only, the plane stresses that act in right angle, horizontally by adjacent part of wall which induce horizontal force toward the wall center and vertically by base restraint, therefore the resultant of these two forces will produce an oblique cracks perpendicular to their opposite action line.

Many plastic shrinkage cracks were initiated in the upper edge of each wall and descended downward about (10-15)cm as shown in Figures (8) to (13). This type of cracks didn’t given any importance in this study.

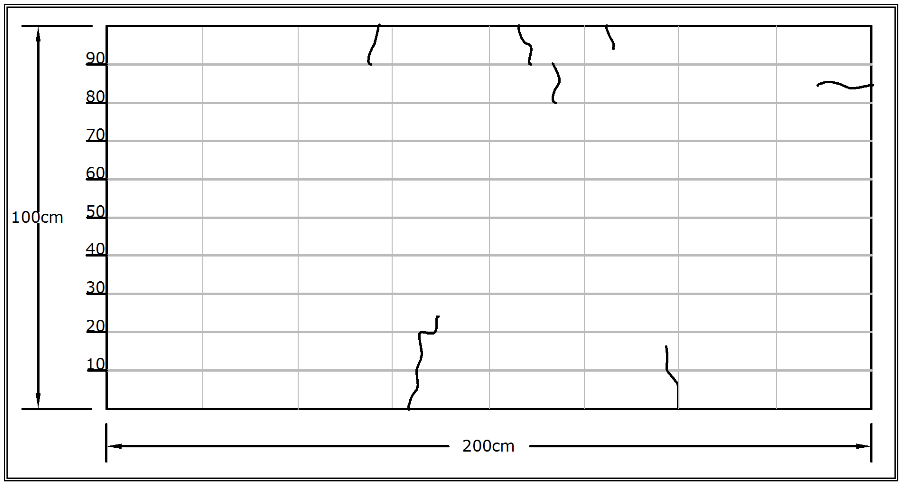


Figure (8) Final cracking pattern of wall (2W) after age of (90) days

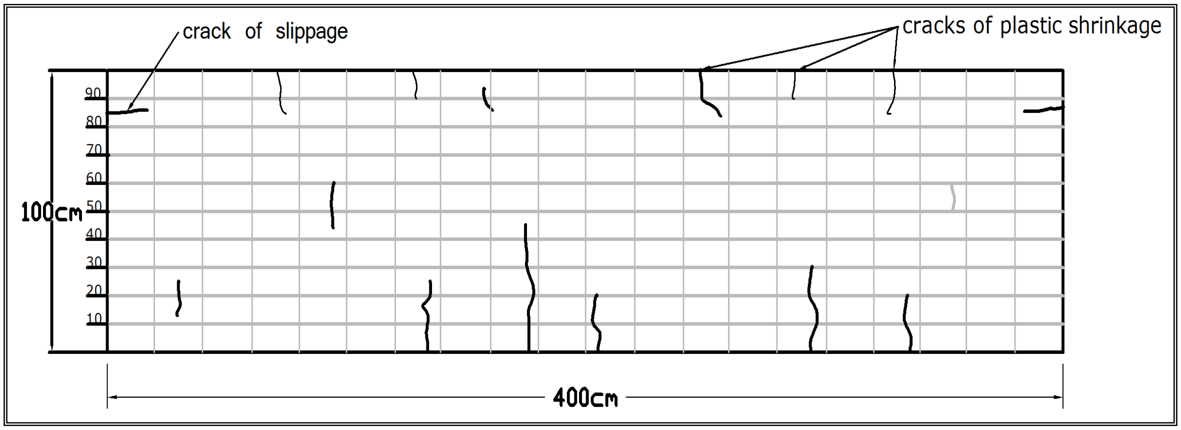


Figure (9) Final cracking pattern of wall (4W) after age of (90) days

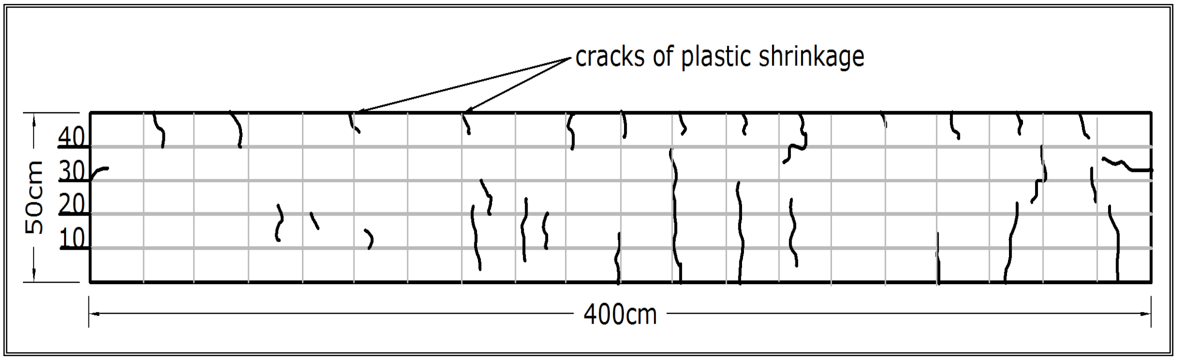
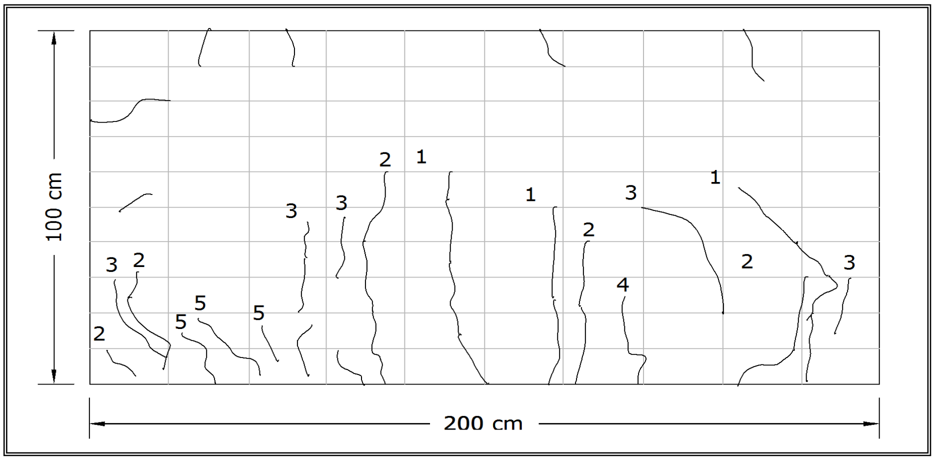
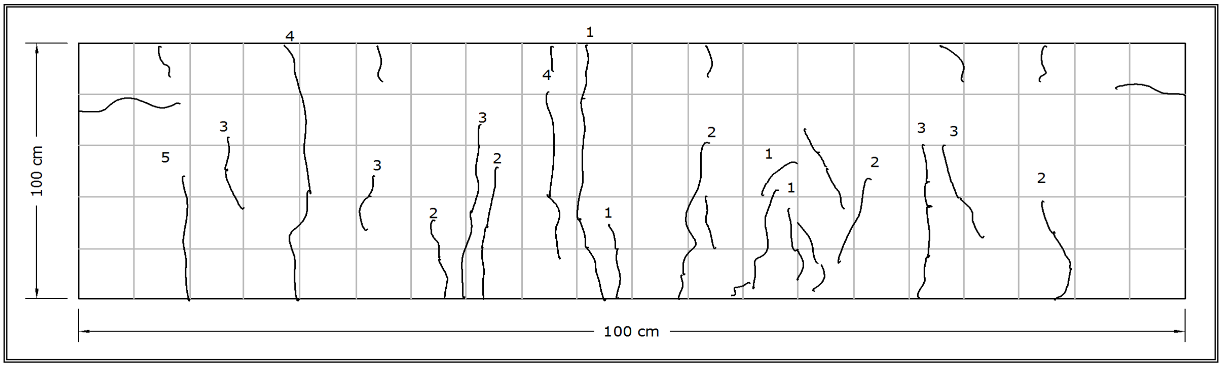


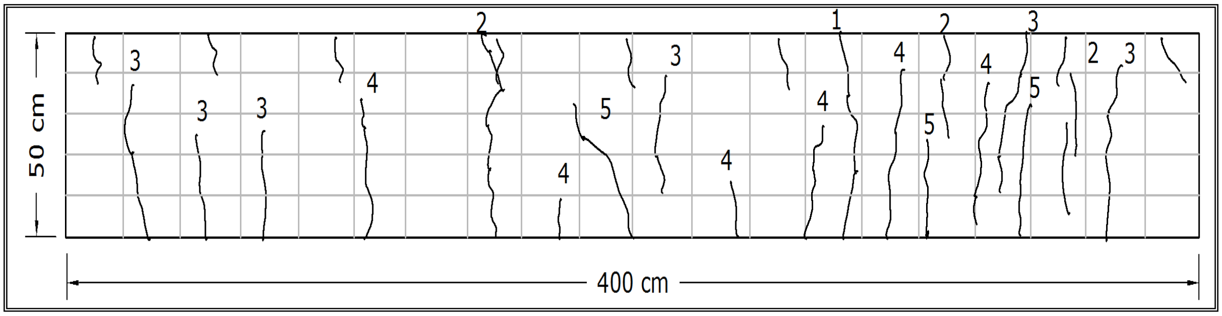
Figure (10) Final cracking pattern of wall (8W) after age of (90) days



Figure(11) Final cracking pattern of wall (2S) after 58 days (Summer set)



Figure(12) Final cracking pattern of wall (4S) after 65 days (Summer set)



Figure(13) Final cracking pattern of wall (8S) after 63 days (Summer set)

Crack spacing:

Table (8) and (9) summarize the minimum, maximum, and average crack spacing that obtained by ***Abbas, 2009*** with comparison with results of ***Stoffer, 1978***. As shown in Figures (8) to (13) of the final cracking pattern of six walls in two sets (winter and Summer), the first set of walls (Winter set) appeared a very poor cracking, the main reason of this results was the very low temperature (16-22) c° with high relative humidity about (40-48)% in the midday where the casting was in January. The second set of Summer were appeared to have a large number of cracks in each wall due to hot and dry weather that increase the rate of drying shrinkage where the casting were in the end of June, with degree of temperature (40) c° and relative humidity (26)%. The information of crack spacing in winter deviate widely corresponding to other results due to incomplete cracking pattern, therefore we can not be depend this results in comparison, whereas the information of crack spacing in Summer it come with the same trend of ***Stoffers, 1978***.

Stoffers, 1978 found for (18) model walls with (L/H) ratios of (6.67-8) which was under compressive prestress and which represented the floor. He observed that the spacing of cracks propagating through the full wall height ranged between (1-1.5)H and this valid for secondary cracks. According to the equation of ***stoffers*** the theoretical crack spacing:

$$S_{ave.}=(0.1-1.2)H \qquad \text{for} \qquad H_c=(0.1-0.8)H$$

Abbas, 2009 found through the Summer results, that the result of average crack spacing:

$$S_{ave.}=(0.16-1.0)H \qquad \text{for} \qquad H_c=(0.1-0.8)H$$

Where $S_{ave.}$ = average crack spacing, H_c = crack height, andH = wall height

Table (8) Minimum, maximum and average crack spacing of Winter walls

Wall name	Height Y/H	$S_{\max}/H$	$S_{\min}/H$	S_{ave}/H	Primary cracks		$S_{ave.Y}/H$ ***Stoffers***
					$S_{\max}/H$	$S_{\min}/H$	
2W	0-0.1	0.7	---	0.7	---	---	0.1-0.15
4W	0-0.2	0.85	0.3	0.48	---	---	0.2-0.3
8W	0-0.2	1.1	0.4	0.6	---	---	0.2-0.3

Table (9) Minimum, maximum and average crack spacing of Summer walls

Wall name	Height Y/H	$S_{\max}/H$	$S_{\min}/H$	S_{ave}/H	Primary cracks		$S_{ave.Y}/H$ ***Stoffers***
					$S_{\max}/H$	$S_{\min}/H$	
M2S	0.0	0.25	0.1	0.16			
	0.1	0.3	0.08	0.2			0.1-0.15
	0.2	0.61	0.09	0.25			0.2-0.3
	0.3	0.4	0.08	0.25			0.3-0.45
	0.4	0.4	0.15	0.25			0.4-0.6
	0.5	0.7	0.2	0.45			0.5-0.75
M4S	0.0	0.6	0.25	0.29	1.0		
	0.2	0.54	0.1	0.29			0.2-0.3
	0.4	0.44	0.1	0.28			0.4-0.6
	0.6	0.85	0.1	0.46			0.6-0.9
	0.8	-	-	1.0			1.20
M8S	0.0	1.0	0.22	0.42	2.4	1.1	
	0.2	0.46	0.1	0.46			0.2-0.3
	0.4	0.57	0.1	0.46			0.4-0.6
	0.6	1.6	0.28	0.86			0.6-0.9
	0.8	1.3	0.3	0.72			0.8-1.2

Figure (14) shows the relation between wall height and the average crack spacing. These relationships were

$$S_{ave} = 0.918\ H \qquad \text{for (L/H=2)}$$
$$S_{ave} = 0.963\ H \qquad \text{for (L/H=4)}$$
$$S_{ave} = 0.877\ H \qquad \text{for (L/H=8)}$$

Abbas, 2009 presented that primary crack spacing ranged between (1.0-2.4)H**.** ***ACI committee 207*** found that for unreinforced concrete member, subjected to base restraint, will attain cracks through the full block height spaced in the neighbourhood of (1-2)times the height of wall block.

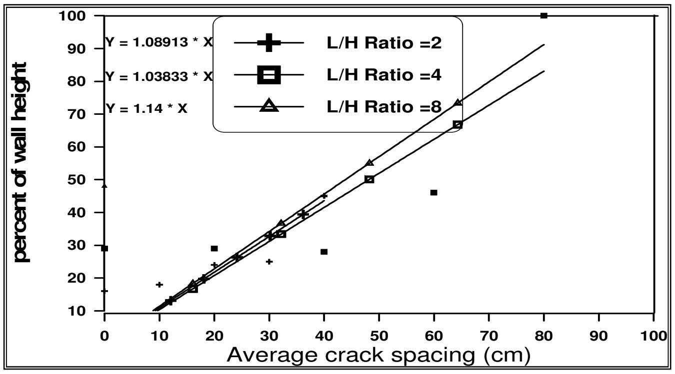


Figure (14) Relation between percent of wall height and the average crack spacing

The obtained results of crack spacing for walls of (L/H=2) were inversed because of the effect of end restraint increased with decreasing of (L/H) ratio as seems, so that a large number of cracks were formed per unit length in wall of end and base restraint with respect to walls of only base restraint as shown in Figure (15).

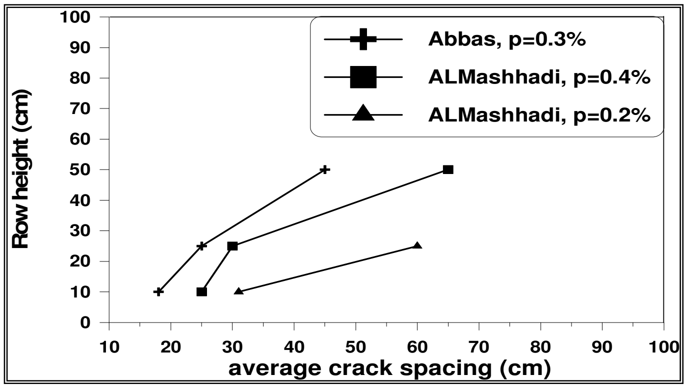


Figure (15) Variation of average crack spacing for end and base restrained walls (observed) and only base restrained walls(ALMashhadi,(L/H)=2)

Also end restraint increase the crack spacing for walls of (L/H=4 and 8), where these results compared with the results of ***ALTamimi, 1987*** and ***Khedher, 1986*** as shown in Figures (16), and (17). The effect of base restraint where is the maximum value in the wall centreline and decreased laterally in the walls of base restraint, therefore the cracks is crowded in the centre of wall and decreased toward the ends subsequently the average crack spacing is low in spite of small crack number, whereas in the walls of end and base restraint the cracks distributed along the wall length subsequently the average crack spacing is high in spite of large crack number.

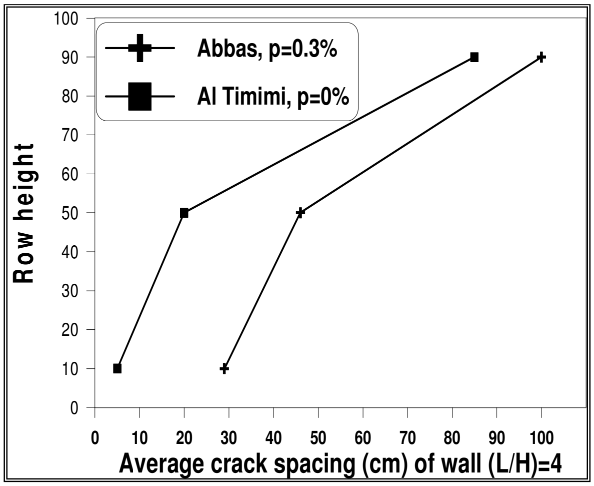


Figure (16) Variation of average crack spacing for end and base restrained walls (observed) and only base restrained walls(ALTamimi,(L/H)=4)

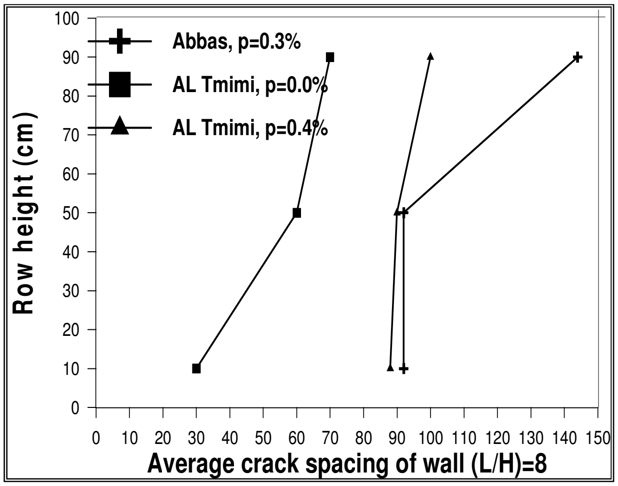


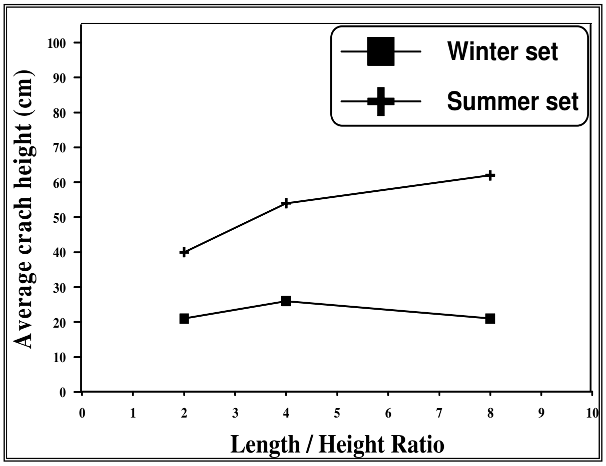
Figure (17) Variation of average crack spacing for end and base restrained walls (observed) and only base restrained walls(ALTamimi,(L/H)=8)

Cracking height:

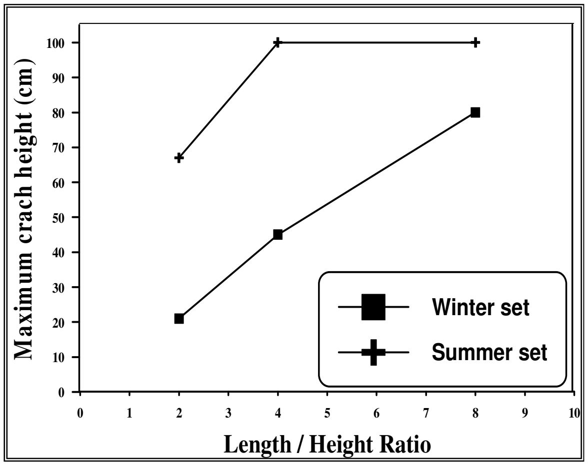
From the experimental results of all walls of (L/H) ratio greater than (2.5) induced secondary and primary cracks, while the walls of (L/H) ratio less than (2.5) (2S) induced only secondary cracks. According to the ***ACI committee 207***, the variation of restraint with height, decreased with increasing of (L/H) ratio, therefore the propagation of cracks height will increase with increasing of (L/H) ratio.

AL Mashhadi, 1989 through his research found the same results for the walls of (L/H) less than (2.5). ***ACI committee 207*** states, governing only secondary shrinkage cracks in walls with length to height ratios less than 2.66.

Figure (18) and (19) shows the relationship of average cracking height and maximum cracking height with (L/H) ratio respectively.



Figure(18) Relationship between the average crack height and L/H ratio



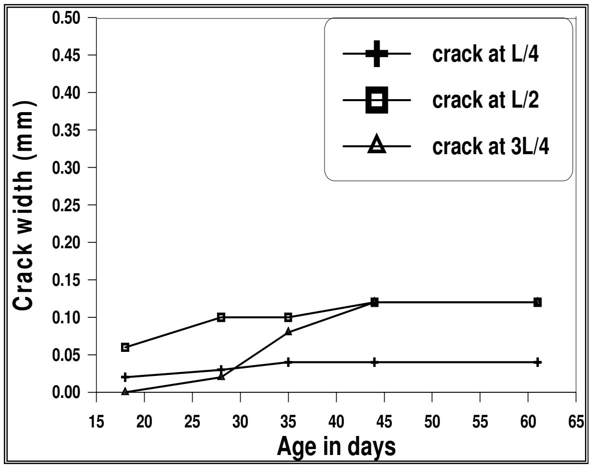
Figure(19) Relationship between the maximum crack height and L/H ratio

crack width:

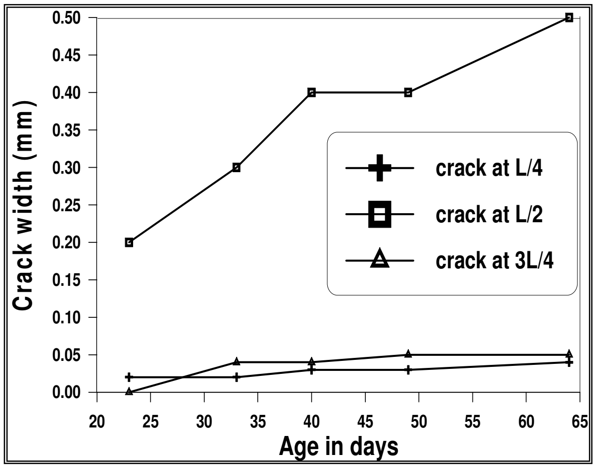
Initiation of cracks width with a beginning value which is about (0.02)mm in the lateral cracks and (0.2)mm in the centreline of the wall according to the degree of base restraint. These cracks widened progressively until a certain constant width in about 60 days occurred. The first crack in each walls observed at age of (30) days in Winter and (14) days in Summer. There are many factors affecting cracking age such as, environmental conditions, roughness of base surface and (L/H) ratio. The high roughness of base surface on which the walls where casted, plays an important role in increasing the number and decreasing the width of cracks. This clear through the results that obtained, where the number of crack is greater and the crack width is smaller in comparison with results that obtained by ***Kheder, 1986*** and ***AL Mashhadi, 1989***, where the contact surface between wall and the restraining base per unit length represented by wall width plus perimeter of four deformed steel bars that welded above the flange, whereas in the previous researches the contact surface per unit length represented by only wall width.

For all investigated walls, the maximum crack width in each wall was that of the earliest crack occurrence. Tables (5) and (6) summarize the final crack widths and heights of maximum crack width.

Figures (20) and (21) show the propagation of crack width with time for a selected cracks of two walls. The crack width and rate of development of each crack for the same wall depend on its position in the wall and consequently the degree of restraint, where the cracks in the centerline of wall larger and developed faster than that near the ends.

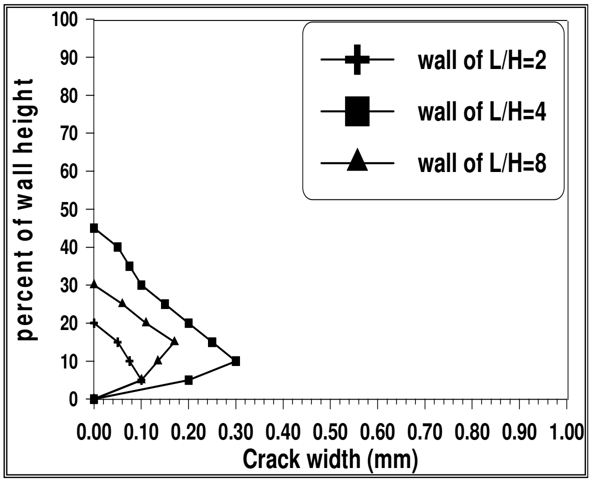


Figure(20) Crack width propagation of wall (2S)
(Distance taken from the left)

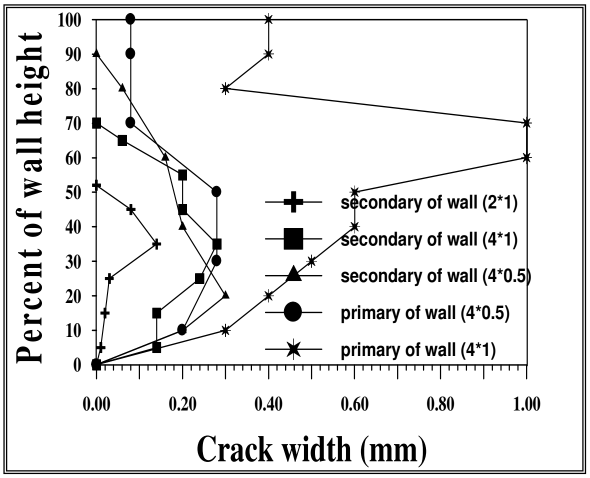


Figure(21) Crack width propagation of wall (4S)
(Distance taken from the left)

The variation of crack width through the wall height in each wall are shown in Figures (22) and (23). All cracks that formed in the walls of Winter set were secondary cracks, while the walls that casted in Summer of (L/H) more than (2) induced primary cracks in addition to secondary cracks, this attributed to the hot and dry weather that lead to increase the rate of drying shrinkage that increase the induced stresses greater than tensile strength development of mortar so that crack developed to the full wall height.



Figure(22) Variation of crack width with crack height, winter set (secondary cracks only)



Figure(23) Variation of crack width with crack height, Summer set (secondary and primary cracks)

Figure (24) shows the level of maximum crack width ($Y_{w.max}$) with respect to crack height for three (L/H) ratios. It has been found that ($Y_{w.max}=0.62H_c$, $0.4H_c$, $0.4H_c$) for ((L/H)= 2, 4, 8) respectively. This indicate the height of maximum crack width proportion inversely with (L/H) ratio to a certain limit, when (L/H=4), beyond that the relation become constant. It can be say that:

$$Y_{w.max} = 0.62H_c \quad \text{for } (L/H=2)$$
$$Y_{w.max} = 0.4H_c \quad \text{for } (L/H>2)$$

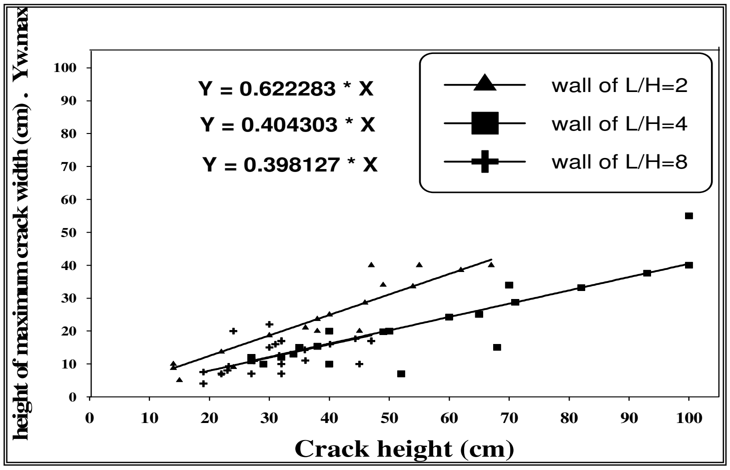


Figure (24) Relationship between Y w.max. and the whole crack length

Al Mashhadi, 1989 found that the relation of height of maximum crack width with crack height is :

$$Y_{w.max}=0.43H_c-5.5 \quad \text{for } (L/H=2)$$

these results compared with the results of ***ALTamimi,1987***,***Khedher,1986,ALMashhadi, 1989,*** and ***ALAttar*** as shown in Figures (25), (26) and (27).In the walls of only base restraint, the effect of base restraint where it is the maximum value in the wall centreline and decreased laterally, therefore the cracks is crowded in the centre of wall and decreased toward the ends subsequently the average crack spacing is low in spite of small crack number, whereas in the walls of end and base restraint, The degree of restraint in the end restrained walls approaches to (100%)(R=1), so that the cracks distributed along the wall length subsequently the average crack spacing is high in spite of large crack number.

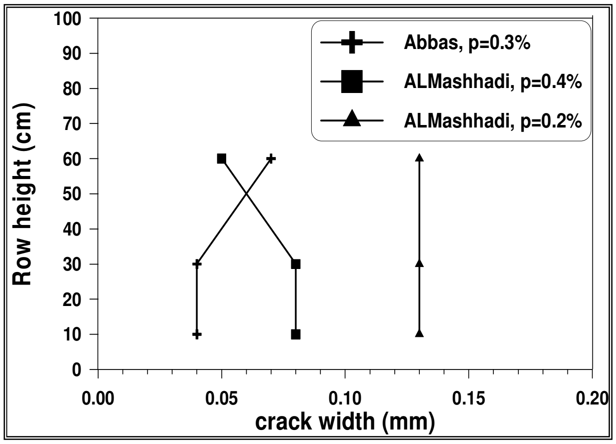


Figure (25) Variation of average crack width for end and base restrained walls (observed) and only base restrained walls(ALMashhadi),(L/H)=2

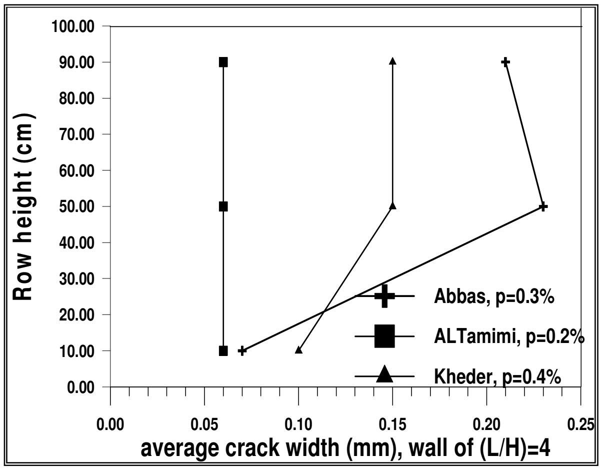


Figure (26) Variation of average crack width for end and base restrained walls (observed) and only base restrained walls(other researchers),(L/H)=4

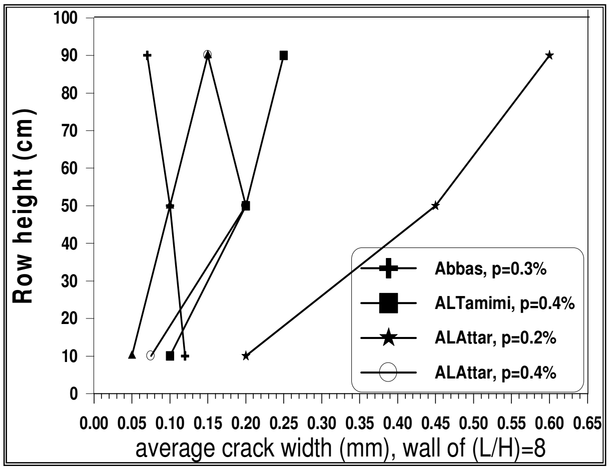


Figure (27) Variation of average crack width for end and base restrained walls (observed) and only base restrained walls of other researchers,(L/H)=8, except ALAttar,L/H=7.5

CONCLUSIONS

Based on the experimental results of base and end restrained walls and the observations presented in the preceding sections, the following conclusions were found:

1. Cracks of the maximum width lies in the centreline of the wall, whereas cracking width of another cracks decreased laterally toward the ends.
2. Height of cracks in the walls of (L/H=2, 4, 8) ranged between (0.2-0.6)H, (0.3-0.8)H, 0.4-0.9)H respectively, where (H) represent wall height.
3. Cracking height for all end and base restrained walls of different (L/H) ratios were similar to that of only base restrained walls of the same (L/H) ratios and proportional mixes in the previous researches.
4. The relationship between cracks spacing and wall height were $S_{ave.}$=(0.92H, 0.96H, 0.88H) for (L/H=2, 4, 8) respectively.
5. Maximum crack width of primary cracks lies in the range (0.3-0.7) of the walls height.
6. The relationship between height of maximum crack width with respect to cracking height was $(Y_{w.\max.} = 0.4Hc, \quad 0.4Hc, \quad 0.62Hc)$ for walls with (L/H=8, 4, 2) respectively, where Hc represent height of crack.
7. For economical purposes, maximum crack width, for walls of any (L/H) ratio, can be controlled by concentrating the horizontal steel reinforcement in the zone of (0.12-0.36) of wall height depending on conclusions of (1, 5).

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