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Mechanical Properties of Polystyrene-Lightweight Concrete

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الخصائص الميكانيكية لخرسانة البوليسترين الخفيفة

ملخص: يتناول هذا البحث العوامل التي تؤثر على مقاومة الضغط لخرسانة البوليسترين الخفيفة، ومن ضمن هذه العوامل التي يشملها البحث نسبة الماء إلى الإسمنت و نسبة البوليسترين إلى الإسمنت و محتوى الإسمنت ومدة المعالجة و العمر و الدمك و الحريق ، بالإضافة إلى المواد المضافة. و قد تم أيضا دراسة العلاقة بين مقاومة الشد لهذا النوع من الخرسانة و ومحتوى الإسمنت. و عند نهاية الدراسة تم عرض طريقة موضحة لتصميم خلطات خرسانة البوليسترين الخفيفة.

المفردات الرئيسية: نسبة البوليسترين إلي الإسمنت — نسبة الماء إلى الإسمنت – مقاومة الضغط

Abstract: In this study, factors, which affect the compressive strength of polystyrene-lightweight concrete, are examined. These factors include water/cement ratio, polystyrene/cement ratio, cement content, curing time, maturity, compaction, fire, and admixtures. Furthermore, the relationship between the tensile strength of this type of concrete and cement content is considered.
At the end of the study, a procedure for designing polystyrene lightweight concrete mixes is outlined.

Keywords: polystyrene/cement ratio; cement content; aggregate content; water/cement ratio

List of Abbreviations:

C Cement Content (kg/m^3) P/S Polystyrene/Cement Ratio
P/C Polystyrene/Cement Ratio W/C Water/Cement Ratio
f_c Compressive Strength (MPa) f_t Tensile Strength (MPa) FM Fineness Modulus AC Aggregate Content (kg/m)
IUG Islamic University- Gaza

1- Introduction

For over fifty years, there have been many attempts to overcome the drawbacks of concrete. Concrete is very heavy, rigid and its thermal and acoustical qualities are not very high. The focus has been to replace aggregates of concrete, sand and gravel with lighter materials. First natural products were utilized such as corn, pumice, schist, cork, pozzuolana, and woods (scraps or sawdust). Later, with greater

knowledge and insulation concerns more materials were used including expanded clay, vermiculite, expanded glass, aluminum, expanded rock, and expanded polystyrene (EPS) [1].
It is convenient to classify the various types of lightweight concrete by their method of production. These are:
(a) By using porous lightweight aggregate of low apparent specific gravity, i.e. lower than 2.6;
(b) By introducing large voids within the concrete or mortar mass;
(c) By omitting the fine aggregate from the mix so that a large number of interstitial; voids are present; normal weight coarse aggregate is generally used.
In essence, the decrease in density of the concrete is obtained by the presence of voids, either in the aggregate, in the mortar or in the interstices among the coarse aggregate particles. It is clear that the presence of these voids reduces the strength of lightweight concrete compared with ordinary, normal weight concrete [2].
There are many advantages to be gained from the use of lightweight concrete. These include lighter loads during construction, reduced self-weight in structures, and increased thermal resistance. Lightweight concrete is generally accepted as concrete having a density of about 1800 kg/m or less [3].
Expanded polystyrene beads are often used as the basis for packaging material. This leads to a large amount of waste material, which is not biodegradable. This material could be granulated and used as a lightweight aggregate for concrete.
The first attempt to introduce the new mix of polystyrene-lightweight concrete was carried out by Dr. Z. Kuhail [4] back in 1996, at the IUG Material and Soil laboratory. Different mix proportions of mortar and virgin polystyrene beads were tested to achieve a homogeneous mix with reasonable compressive strength. Some useful findings were concluded which covered the feasible ranges of W/C ratio and P/C ratio. Furthermore, a new mix design procedure had been set. Commercially this mix was patented in Palestine and currently used for producing the ***Polyc*** hollow blocks.
Study of commercial literature shows that polystyrene is being used as aggregate in lightweight concrete systems. The lightweight concrete is available as precast panels or hollow blocks, which can be easily

handled, cut with power tools or handsaws, and erected quickly and simply. Alternatively, expanded polystyrene (EPS) can be used at the time of mixing concrete. The beads are virgin EPS, not recycled [1,4,6].

A literature survey found limited number research results with regard to polystyrene concrete made from either virgin or recycled EPS. One of these researches was carried out by Sri Ravindrarajah and Tuck [7]. They investigated the compressive strength, tensile strength, static modulus of elasticity, ultrasonic pulse velocity, drying shrinkage and chemical resistance of BST polystyrene concrete with densities of 1300 kg/m and 1400 kg/m . They also investigated the inclusion of silica fume in the mixes.

Work was carried out by the Cement and Concrete Association of New Zealand in 1991 and 1994 [8]. This limited study, which examined the strengths and some drying shrinkage of recycled EPS concrete with densities ranging from 700 to 1700 kg/m , showed that waste granulated polystyrene can be used to manufacture lightweight concrete with similar strength to polystyrene bead concrete.

A study of concrete made with polystyrene beads as aggregate was carried out by Park and Chisholm [3]. Three different densities were investigated, and at each density, mixes both with and without fly ash were examined. It was found that polystyrene concrete is very prone to segregation. It has a low compressive strength and a relatively high drying shrinkage for the densities investigated. Thermal conductivity testing showed that the lighter is the concrete, the lower is the thermal conductivity. Adding flying ash to the mixes decreased the water demand, and hence the density and shrinkage, but it also caused a significant compressive strength reduction.

The present research is concerned with studying the major factors which affect the compressive strength of polystyrene-lightweight concrete, establishing a relation between the tensile and compressive strength, and setting out a procedure for designing polystyrene-lightweight concrete mixes.

2- Testing Program:
2-1 Materials
The materials used in preparing all of the concrete specimens were as follows:

Cement: ordinary Portland cement, manufactured by the Israeli company, “Nesher” with fly ash of up to 10 % of cement weight, and conforms to ASTM C150. It is the only cement type available in Gaza market. Table 1 shows the mechanical properties of the cement used.
Sand: Gaza dune sand with fineness modulus FM = 2.68.

Coarse Aggregates: crushed limestone, angular in shape and rough in texture, obtained from the West Bank quarries which is the only aggregate source available in Gaza market, with fineness modulus FM = 5.98.

Mixing Water: drinking water from the piped water supply system in IUG is used in preparing all of the concrete mixes, and found to be conforming to BS 3148:1980.

Polystyrene Beads: raw fire retardant, polystyrene beads containing an expanding agent. These beads are subjected to steam to expand and form a cellular structure. The expanded beads are left out in the air for a few hours before they are used in the mix to allow the pressure within the beads to equalize with the outside air. The expanded beads have an apparent density of 16-27 kg/m , and diameters ranging from 1.5 to 3.0 mm.

Admixture: PLASTMIX42, a super-plasticizing, retarding admixture is used in some of the mixes used in the study.

Table 1: Mechanical properties of cement

Test		Result
Compressive strength (Mpa)	3-day	19.7
	7-day	25.1
Normal consistency (%)		25.6
Initial setting time		135 min
Final setting time		280 min
Fineness		3550 cm^2/gr
Soundness		1.5 mm

2-2 Mix Proportions

The volume method is used to proportion the polystyrene-lightweight mixes. The aggregate content is chosen, together with the cement content and the water cement ratio, guided by Table 2. The volume of polystyrene beads is determined by subtracting the total volume of water, cement, and aggregate from the unit volume, set here as 1 m .

Table 2: Limits of factors controlling mix design

Quantity	Limits
W/C ratio	0.40 - 0.50
Cement content (kg/m)	250 - 600
Aggregate content (kg/m)	500 - 1000
Polystyrene content (m /m)	0.30 - 0.70

Out of the large number of prepared polystyrene-lightweight concrete mixes, thirty-six mix proportions are shown in Table 3. These mixes are accomplished by using water/cement ratios of 0.35, 0.40, 0.45, and 0.50, three aggregate contents of 500, 750, and 1000 kg/m3, three cement contents of 350, 400,and 450 kg/m3 for each of the three ratios.

Mechanical Properties of Polystyrene

Table 3: Some of the polystyrene-lightweight concrete mixes used in the study

No.	W/C	Agg. (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (liters)	Polystyrene (m^3/m^3)	P/S (volume)	Theoretical Density (kg/m^3)
1	0.35	500	200	350	122.5	0.58	1.97	984.08
2	0.35	750	300	350	122.5	0.49	1.10	1232.21
3	0.35	1000	400	350	122.5	0.39	0.67	1480.34
4	0.35	500	200	400	140	0.55	1.86	1050.91
5	0.35	750	300	400	140	0.45	1.02	1299.04
6	0.35	1000	400	400	140	0.36	0.61	1547.17
7	0.35	500	200	450	157.5	0.51	1.74	1117.75
8	0.35	750	300	450	157.5	0.42	0.95	1365.87
9	0.35	1000	400	450	157.5	0.33	0.55	1614.00
10	0.4	500	200	350	140	0.56	1.91	1001.23
11	0.4	750	300	350	140	0.47	1.06	1249.36
12	0.4	1000	400	350	140	0.37	0.64	1497.49
13	0.4	500	200	400	160	0.53	1.79	1070.51
14	0.4	750	300	400	160	0.43	0.98	1318.64
15	0.4	1000	400	400	160	0.34	0.58	1566.77
16	0.4	500	200	450	180	0.49	1.67	1139.80
17	0.4	750	300	450	180	0.40	0.90	1387.92
18	0.4	1000	400	450	180	0.30	0.51	1636.05
19	0.45	500	200	350	157.5	0.54	1.85	1018.38
20	0.45	750	300	350	157.5	0.45	1.02	1266.51
21	0.45	1000	400	350	157.5	0.36	0.61	1514.64
22	0.45	500	200	400	180	0.51	1.72	1090.11
23	0.45	750	300	400	180	0.41	0.93	1338.24
24	0.45	1000	400	400	180	0.32	0.54	1586.37
25	0.45	500	200	450	202.5	0.47	1.59	1161.85
26	0.45	750	300	450	202.5	0.37	0.85	1409.97
27	0.45	1000	400	450	202.5	0.28	0.48	1658.10
28	0.5	500	200	350	175	0.53	1.79	1035.53
29	0.5	750	300	350	175	0.43	0.98	1283.66
30	0.5	1000	400	350	175	0.34	0.58	1531.79
31	0.5	500	200	400	200	0.49	1.65	1109.71
32	0.5	750	300	400	200	0.39	0.89	1357.84
33	0.5	1000	400	400	200	0.30	0.51	1605.97
34	0.5	500	200	450	225	0.44	1.51	1183.90
35	0.5	750	300	450	225	0.35	0.80	1432.02
36	0.5	1000	400	450	225	0.26	0.44	1680.15

2-3 Specimens

For compressive strength evaluation, cubic samples of 10 cm are used. The compression test is carried according to BS 1881: Part 116; 1983. On the other hand, 15 cm x 15 cm x 75 cm beam samples are used for tensile strength evaluation, and the test is carried out according to BS 5328: 1991 as a compliance test.

2-4 Curing

Specimens are cured 24 hours after preparation and demoulding by placing them in a curing tank at a temperature of 25° for the period that precedes laboratory testing.

3- Test Results:

3-1 Compressive Strength:

Compressive strength is a convenient way of characterizing concrete because most of the desirable properties improve with an increase in compressive strength.

3-1-1 Water/cement ratio:

Table 4 and Figures 1 to 3 illustrate the relationship between compressive strength and water/cement ratio for different cement and aggregate contents.

Table 4: Compressive strength vs. water/cement ratio

AC	C	250	300	350	400	450	500	550
	W/C	Compressive strength f_c in MPa						
500	0.40	7.1	7.4	9.8	11.6	13.1	14.1	15.2
	0.45	5.2	6.5	8.2	10.1	11.5	12.4	14.5
	0.50	3.1	5.2	6.2	9.2	10.2	11.5	13.2
	0.55	2.1	3.4	5.1	7.1	8.5	9.1	11.1
750	0.40	8.4	9.8	12.4	14.9	16.8	18.5	19.8
	0.45	6.99	8.51	11.2	13.1	14.9	16.4	18.5
	0.50	3.5	6.8	9.0	11.9	13.1	15.0	17.0
	0.55	2.8	4.7	6.3	9.0	10.5	12.4	14.2
1000	0.40	10.7	12.5	15.3	18.5	20.2	21.9	24.2
	0.45	8.7	11.7	14.5	17.1	19.1	20.3	22.4
	0.50	5.2	9.85	12.0	15.3	17.2	19.5	20.9
	0.55	3.64	6.3	8.7	12.0	14.0	17.5	19.5

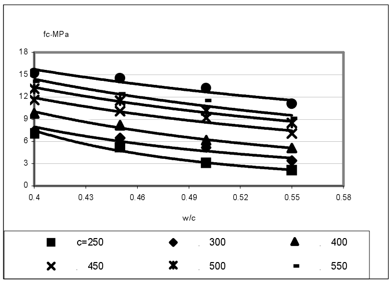

Figure 1: relation between the 28-day compressive stress and w/c ratio, AC =500 kg/m^3

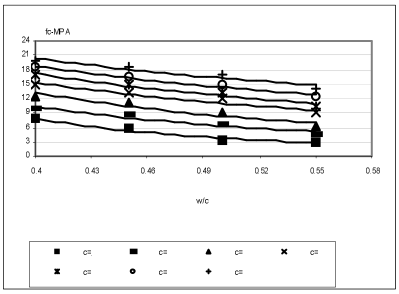

Figure2: relation between the 28-day compressive stress and w/c ratio, AC =750 kg/m3

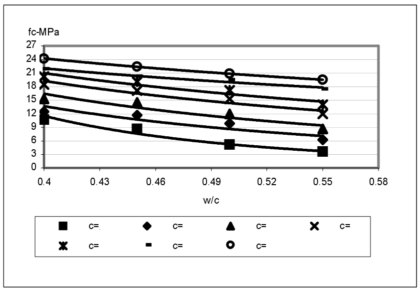

Figure 3: relationship between the 28-day compressive stress and w/c ratio, AC =1000 kg/m3

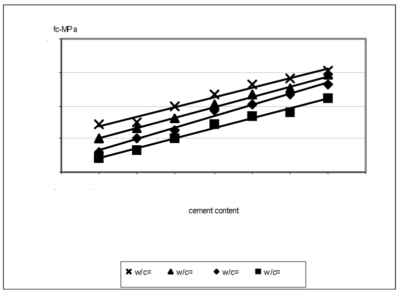

Figure 4: relationship between the 28-day compressive stress and cement content, AC =500 kg/m3

3-1-2 Cement content:

Figures 4 to 6 represent the relationship between compressive strength and cement content for different water/cement ratios, and aggregate contents.

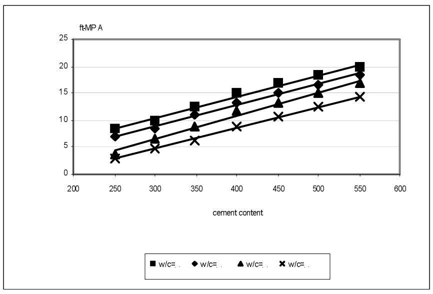

Figure 5: relationship between the 28-day compressive stress and cement content, AC =750 kg/m3

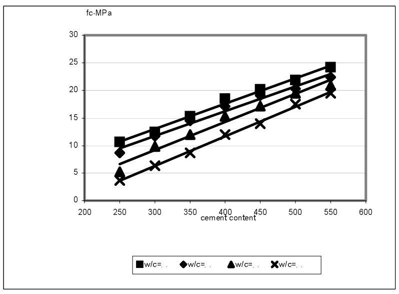

Figure 6: relationship between the 28-day compressive stress and cement content, AC =1000 kg/m3

3-1-3 Polystyrene/cement ratio:

Table 5 and Figures 7 to 10 illustrate the relationship between compressive strength and polystyrene/cement ratio for different water/cement ratios and aggregate contents.

Table 5: Compressive strength vs. polystyrene/cement ratio

W/C	AC=500 kg/m^3		AC = 750 kg/m		AC = 1000 kg/m	
	P/C	f_c	P/C	f_c	P/C	f_c
0.40	7.97	7.1	6.79	8.40	5.6	10.7
	6.27	7.4	5.28	9.80	4.29	12.5
	5.05	9.8	4.20	12.4	3.36	15.3
	4.13	11.6	3.39	14.9	2.65	18.5
	3.42	13.1	2.7	16.8	2.11	20.2
	2.86	14.1	2.26	18.5	1.67	21.9
	2.39	15.2	1.85	19.8	1.31	24.2
0.45	7.81	5.2	6.63	6.99	5.45	8.70
	6.11	6.5	5.12	8.51	4.14	11.7
	4.89	8.2	4.04	11.2	3.20	14.5
	3.98	10.1	3.24	13.1	2.50	17.1
	3.27	11.5	2.61	14.9	1.95	19.1
	2.7	12.4	2.11	16.4	1.51	20.3
	2.23	14.5	1.69	18.5	1.16	22.4
0.50	7.66	3.10	5.29	5.20	6.47	3.50
	5.95	4.15	3.98	9.85	4.96	7.74
	4.73	6.20	3.04	12.0	3.89	10.66
	3.82	9.20	2.34	15.3	3.08	11.9
	3.11	10.2	1.79	17.2	2.45	14.34
	2.54	11.5	1.36	19.5	1.95	17.17
	2.08	13.5	1.00	20.9	1.54	18.21
0.55	7.5	2.20	6.31	2.80	5.13	3.64
	5.79	3.40	4.81	4.70	3.82	6.30
	4.58	5.10	3.73	6.30	2.88	8.70
	3.66	7.10	2.92	9.00	2.18	12.0
	2.95	8.50	2.29	10.5	1.64	14.0

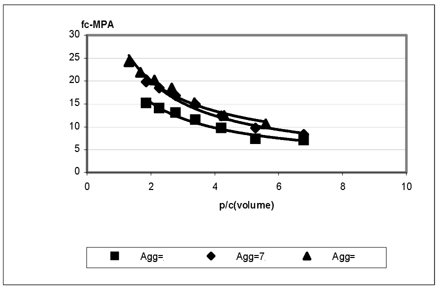

Figure 7: relation between 28-day compressive stress and p/c ratio, for w/c =0.40

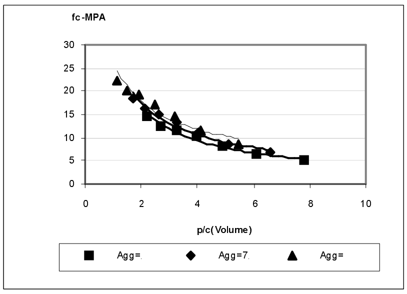

Figure 8: relation between 28-day compressive stress and p/c ratio, for w/c =0.45

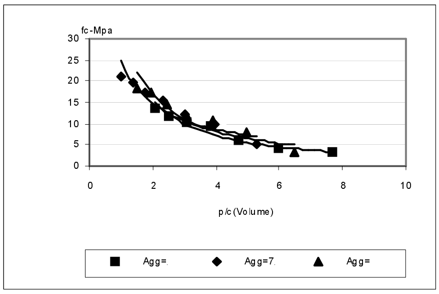

Figure 9: relation between 28-day compressive stress and p/c ratio, for w/c =0.50

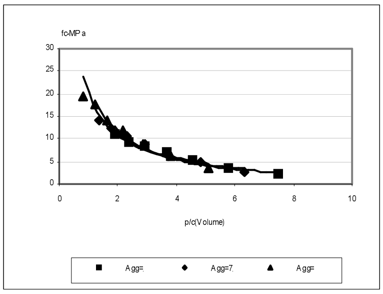

Figure 10: relation between 28-day compressive stress and p/c ratio, for w/c =0.50

3-1-4 Maturity:

Table 6 and Figures 11 to 14 illustrate the development of compressive strength, tested at 3, 7, 14, and 28 days, for different water/cement ratios and aggregate contents.

Table 6: Maturity of polystyrene-light weight concrete

AC	W/C	C= 450				C= 500			
		Compressive strength f_c in MPa				Compressive strength f_c in MPa			
		3-day	7-day	14-day	28-day	3-day	7-day	14-day	28-day
500	0.40	5.6	8.2	12.2	13.1	6.4	8.9	13.3	14.1
	0.45	5.1	7.3	10.7	11.5	5.6	7.8	11.2	12.4
	0.50	4.3	6.4	9.6	10.2	5.2	7.3	10.3	11.5
	0.55	4.0	5.4	8.2	8.5	4.1	5.8	8.55	9.1
	0.40	6.7	10.3	15.3	16.8	8.4	11.6	14.2	18.5

750	0.45	6.1	9.5	14.2	14.9	7.4	10.3	15.6	16.4
	0.50	5.6	8.6	12.3	13.1	6.8	9.5	13.5	15
	0.55	4.3	7.3	9.63	10.5	6.1	7.8	11.2	12.4
1000	0.40	8.4	12.1	18.3	20.2	9.9	13.8	20.6	21.9
	0.45	8.1	12.2	17.6	19.1	9.5	12.8	18.9	20.3
	0.50	7.3	10.3	16.2	17.2	8.9	12.3	18.0	19.5
	0.55	6.2	8.7	13.1	14.0	7.7	11.1	16.5	17.5

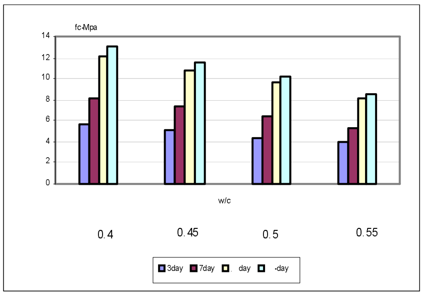

Figure 11: development of compressive strength, for C = 450 kg/m^3 and AC = 500 kg/m^3

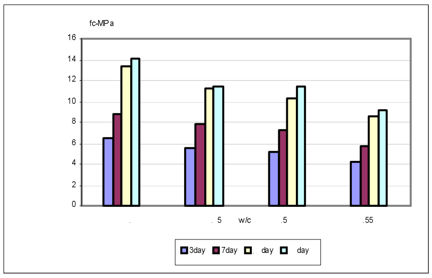

Figure 12: development of compressive strength, for C = 500 kg/m3 and AC = 500 kg/m3

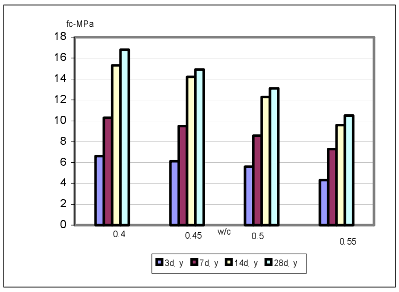

Figure 13: development of compressive strength, for C = 450 kg/m3 and AC = 750 kg/m3

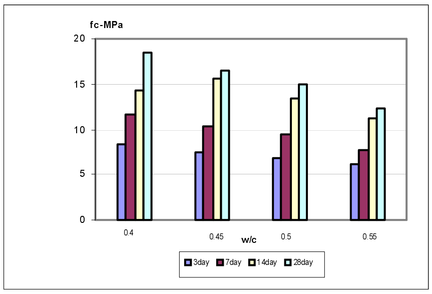

Figure 14: development of compressive strength, for C = 500 kg/m3 and AC = 750 kg/m3

3-1-5 Curing:

Table 7 and Figure 15 show the effects of curing on 28-day compressive strength.

Table 7: Compressive strength vs. curing period

AC	Mix	W/C	C= 500				
			Compressive strength f_c in MPa				
			Curing period				
			0 days	3 days	14 days	20 days	28 days
750	1	0.40	6.5	9.2	16.1	17.1	18.5
	2	0.45	4.2	6.2	11.9	15.2	16.4
	3	0.50	3.1	5.4	9.40	14.4	15.9

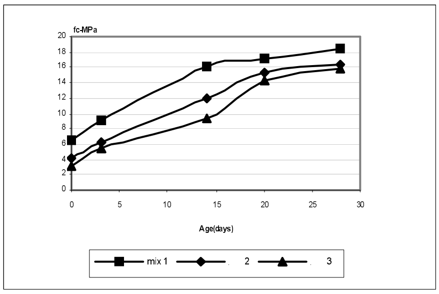

Figure 15: Effect of curing on compressive strength

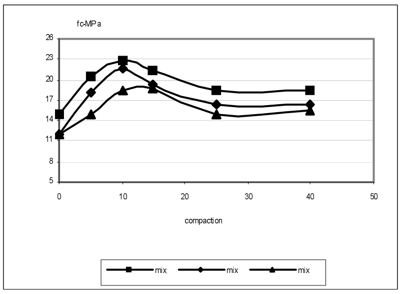

Figure 16: Effect of compaction on compressive strength

3-1-6 Compaction:

Table 8 and Figure 16 show the effects of compaction on 28-day compressive strength.

Table 8: Compressive strength vs. compaction

AC	Mix	W/C	C= 500					
			Compressive strength f_c in MPa					
			Strokes					
			0	5	10	15	25	40
750	1	0.40	14.8	20.3	22.9	21.3	18.5	18.5
	2	0.45	12.1	18.1	21.5	19.3	16.4	16.4
	3	0.50	12.1	14.9	18.5	18.7	14.9	15.5

3-1-7 Fire:

Table 9 and Figure 17 show the effects of fire on 28-day compressive strength.

Table 9: Compressive strength deterioration factor

Time (Minutes)	Polystyrene Concrete	Deterioration Factor	Ordinary Concrete	Deterioration Factor
0	18.5	0.00	32.0	0.00
15	10.5	24.6	22.3	18.8
30	7.20	33.2	18.4	24.6
45	4.10	40.8	10.2	34.5
60	3.50	44.3	8.70	39.5

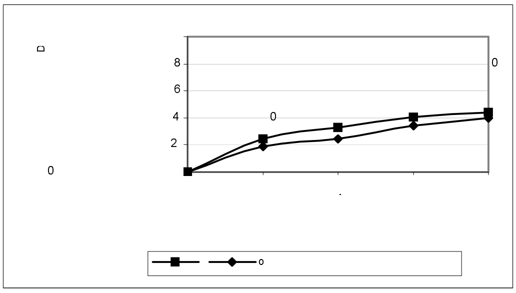

Figure 17: deterioration factor for ordinary and polystyrene lightweight concrete

3-1-8 Admixture

Table 10-a, 10-b, and Figures 18 to 25 illustrate the effect of the used admixture on compressive strength.

Table 10-a: 28-day compressive strength using admixture

AC	C	250	300	350	400	450	500	550
	W/C	Compressive strength f_c in MPa						
500	0.40	6.70	7.20	9.10	11.5	12.9	13.1	15.1
	0.45	4.80	6.40	7.85	10.0	10.9	11.5	14.2
	0.50	3.00	5.20	6.20	9.15	9.80	10.7	13.0
	0.55	2.20	3.20	4.52	6.80	7.90	8.6	11.2
750	0.40	8.10	9.20	10.6	14.3	16.6	18.0	19.9
	0.45	6.82	8.20	10.9	12.6	14.0	15.6	17.3
	0.50	3.40	6.30	8.20	11.5	13.0	14.6	16.5
	0.55	2.76	4.5	5.60	8.96	10.3	12.2	13.2
1000	0.40	8.50	12.3	14.9	17.6	19.5	20.8	22.1
	0.45	7.60	11.6	14.5	16.3	18.6	19.2	19.6
	0.50	4.60	9.82	11.9	15.3	17.1	18.9	18.6
	0.55	3.20	5.40	7.8	11.2	13.5	17.4	19.5

Table 10-b: 7-day compressive strength using admixture

AC	W/C	C= 450 Compressive strength f_c in MPa		C= 500 Compressive strength f_c in MPa	
		No admixture	With admixture	No admixture	With admixture
500	0.40	8.20	10.2	8.80	9.20
	0.45	7.30	9.30	7.80	8.10
	0.50	6.40	7.60	7.20	7.95
	0.55	5.35	6.20	5.70	6.50
750	0.40	10.3	11.6	11.6	13.2
	0.45	9.50	12.5	10.3	11.5
	0.50	8.60	9.60	9.40	9.40
	0.55	7.30	8.70	7.80	8.50
1000	0.40	12.1	13.3	13.0	14.2
	0.45	12.2	13.1	12.8	13.5
	0.50	10.3	11.3	12.3	13.1
	0.55	8.70	9.60	11.12	12.1

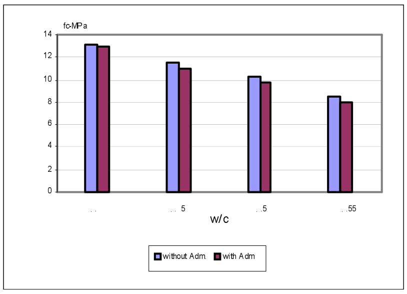

Figure 18: 28-day compressive strength, with and without admixture, for C = 450 kg/m^3 and AC = 500 kg/m^3

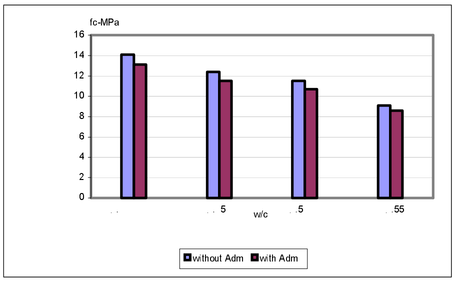

Figure 19: 28-day compressive strength, with and without admixture, for C = 500 kg/m3 and AC = 500 kg/m3

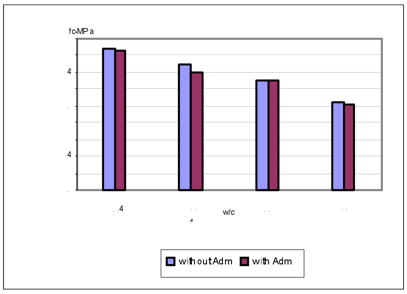

Figure 20: 28-day compressive strength, with and without admixture, for C = 450 kg/m^3 and AC = 750 kg/m^3

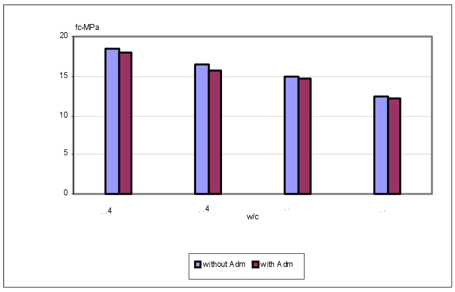

Figure 21: 28-day compressive strength, with and without admixture, for C = 500 kg/m^3 and AC = 750 kg/m^3

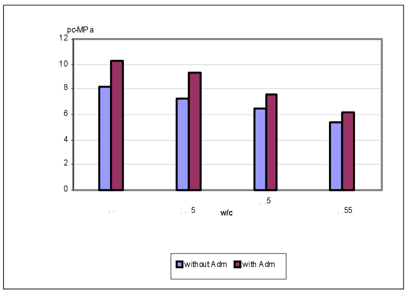

Figure 22: 7-day compressive strength, with and without admixture, for C = 450 kg/m^3 and AC = 500 kg/m^3

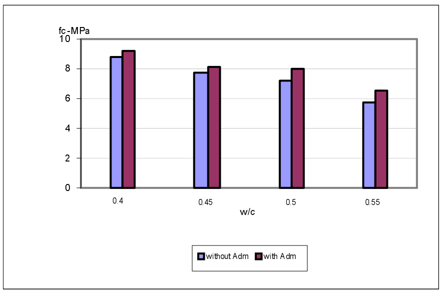

Figure 23: 7-day compressive strength, with and without admixture, for C = 500 kg/m3 and AC = 500 kg/m3

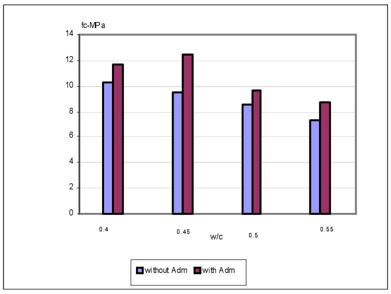

Figure 24: 7-day compressive strength, with and without admixture, for C = 450 kg/m^3 and AC = 750 kg/m^3

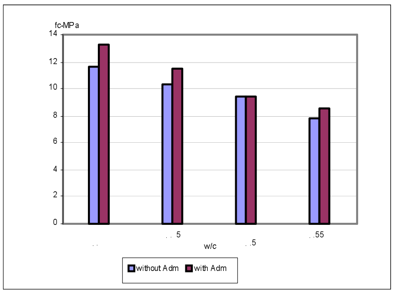

Figure 25: 7-day compressive strength, with and without admixture, for C = 500 kg/m^3 and AC = 750 kg/m^3

3-1-9 Development of strength beyond 28days:

Table 11 and Figure 26 show the compressive strength at 28 days, 2 months, and 3 months.

Table 11: Compressive strength development

AC	W/C	C= 450			C= 500		
		Compressive strength f_c in MPa			Compressive strength f_c in MPa		
		28-day	2-month	3-month	28-day	2-month	3-month
500	0.40	13.1	14.1	15.6	14.1	15.7	17.1
	0.45	11.5	12.5	13.6	12.4	13.6	15.1
	0.50	10.2	11.3	12.1	11.5	12.5	13.5
	0.55	8.50	9.60	11.0	9.10	10.2	10.5
750	0.40	16.8	18.5	20.1	18.5	19.9	22.1
	0.45	14.9	16.1	17.6	16.4	18.3	19.5
	0.50	13.1	14.3	16.2	15.0	16.7	17.9
	0.55	10.5	11.6	12.4	12.4	13.8	15.1
1000	0.40	20.2	22.5	23.8	21.9	24.5	26.3
	0.45	19.1	21.0	22.5	20.3	23.1	24.3
	0.50	17.2	19.3	20.3	19.5	21.7	23.4
	0.55	14	14.9	16.7	17.5	19.3	20.9

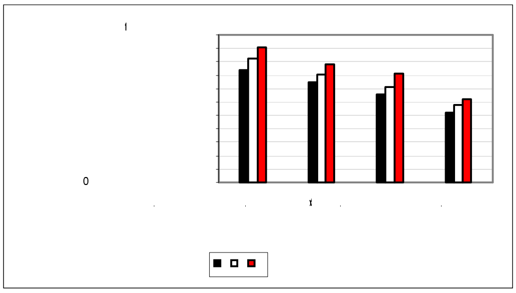

Figure 26: compressive strength at 28 days, 2 months, and 3 months for C = 450 kg/m3 and AC = 750 kg/m3

3-2 Tensile Strength Test Results:

In reinforced concrete design of cracked elements, concrete strength in tension is neglected. However, tensile strength of concrete cannot be avoided since it is related to its shear resistance.

Table 12 shows tensile strength test results f_t, using flexural testing for four different values of water/cement ratio; 0.40, 0.45, 0.50, and 0.55, and three aggregate contents; 500, 750, and 1000 kg/m^3. Figures 27 to 30 show the relation between tensile strength of Polystyrene-light weight concrete represented by modulus of rupture and cement contents for four different values of water/cement ratios.

Table 12: Tensile Strength vs. water/cement ratio

AC	C	250	300	350	400	450	500	550
	W/C	Flexural strength f_t in MPa						
500	0.40	0.41	0.45	0.65	0.67	0.81	0.89	0.92
	0.45	0.31	0.40	0.54	0.62	0.72	0.78	0.90
	0.50	0.25	0.32	0.39	0.55	0.63	0.71	0.81
	0.55	0.16	0.21	0.35	0.42	0.57	0.65	0.75
750	0.40	0.62	0.56	0.81	0.88	1.10	1.20	1.20
	0.45	0.51	0.49	0.68	0.75	1.20	1.10	1.11
	0.50	0.32	0.38	0.61	0.71	0.81	0.90	1.12
	0.55	0.23	0.25	0.41	0.53	0.65	0.87	0.92
1000	0.40	0.60	0.81	1.20	1.00	1.30	1.40	1.56
	0.45	0.61	0.89	1.10	1.10	1.20	1.35	1.34
	0.50	0.35	0.61	0.80	0.80	1.10	1.24	1.32
	0.55	0.23	0.40	0.61	0.75	0.95	1.11	1.21

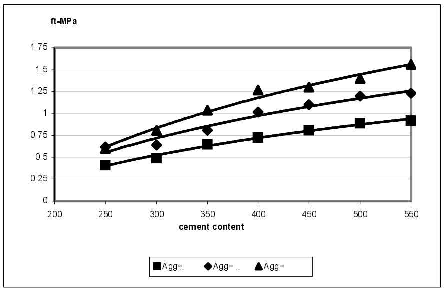

Figure 27: relation between the 28-day tensile stress and the cement content, for w/c =0.40

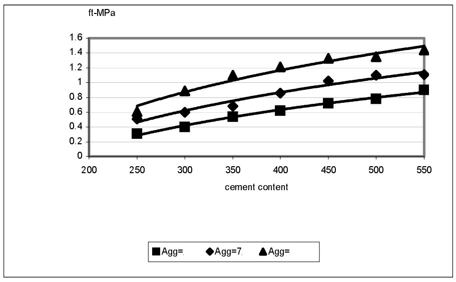

Figure 28: relation between the 28-day tensile stress and the cement content, for w/c =0.45

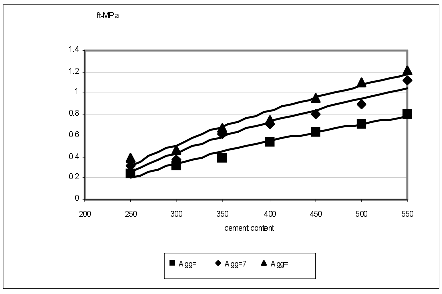

Figure 29: relation between the 28-day tensile stress and the cement content, for w/c =0.50

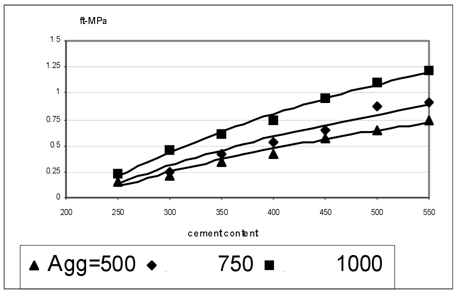

Figure 30: relation between the 28-day tensile stress and the cement content, for w/c =0.55

3-3 Actual and theoretical densities:

Table 13 and Figure 31 show the differences between actual and theoretical densities.

Table 13: Actual and theoretical densities of polystyrene-lightweight concrete

Agg.	W/c	Cement=400		Cement=500	
		Theoretical	Actual	Theoretical	Actual
500	0.4	1060	1290	1200	1431
	0.45	1080	1317	1225	1455
	0.5	1100	1342	1250	1485
	0.55	1120	1365	1275	1517
750	0.4	1310	1599	1450	1731
	0.45	1330	1622	1475	1750
	0.5	1350	1645	1500	1786
	0.55	1370	1670	1525	1817

Mechanical Properties of Polystyrene

1000	0.4	1560	1910	1700	2020
	0.45	1580	1927	1725	2046
	0.5	1600	1952	1750	2081
	0.55	1620	1970	1775	2114

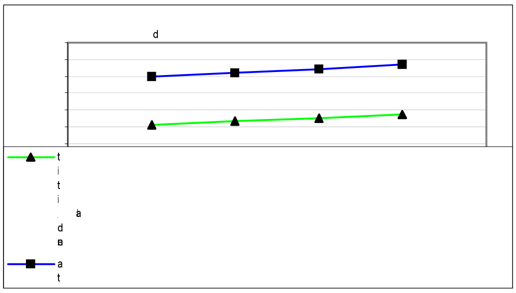

Figure 31: actual and theoretical densities for C = 400kg/m^3 , and AC =750kg/m^3

4- Discussion of Results

4-1 Compressive strength

4-1-1 Effects of water/cement ratio and cement content

The compressive strength increases as the w/c decreases, as the amount of aggregate increases, and as the cement content increases.

The compressive strength of polystyrene-lightweight concrete is much lower than normal weight concrete due to the weak bond between the polystyrene beads and the cement paste, and weakness of the beads themselves.

4-1-2 Effect of polystyrene/cement ratio

The compressive strength is reduced as long as the polystyrene/cement ratio is increased.

4-1-3 Effect of maturity

As expected, the compressive strength of polystyrene-lightweight concrete increases with time. The 3-day compressive strength is about 40 % of the 28-day strength, while the 7-day strength is about 60 % of the 28-day strength, and the 14-day strength is about 90 % of the 28-day strength.

4-1-4 Effect of curing

From Figure 15, it is clear that the effect of curing is significant up to a period of two weeks, and diminishes for the two weeks that follows.

4-1-5 Effect of compaction

From Figure 16, it is obvious that 10 strokes is the ideal number of accomplishing the highest compressive strength.

4-1-6 Effect of fire

From Figure 17 the effect of fire on compressive strength of polystyrene-lightweight concrete is almost the same as for normal-weight concrete. This effect is measured by the deterioration factor, which is the ratio of the deteriorated compressive strength to the compressive strength of concrete not subjected to fire. The deterioration factor for polystyrene-lightweight concrete is larger than that for normal-weight concrete, and the difference gets smaller with time, as it decreases from 30 % at 15 minutes to 12 % at 60 minutes.

4-1-7 Effect of admixtures

From Figures 18 through 25 it can be concluded that when using the PLASTMIX42 admixture the 7-day strength is increased, while the 28-day is decreased.

4-1-8 Effect of age

From Table 11, the compressive strength at 2 months is about 110 % of the 28-day compressive strength, while at 3 months, it is about 120 % of the 28-day compressive strength.

4-2 Tensile strength

The tensile strength of polystyrene-lightweight concrete, represented by its modulus of rupture, increases as the cement content or the amount of aggregates is increased, as shown in Figures 27 to 30. Furthermore, the tensile strength is inversely proportional to the water/cement ratio, as shown in Table 12.

The tensile strength ranges from 5.75 % to 7.5 % of its compressive strength, compared with 8 % to 15 % in normal-weight concrete. The substantial reduction in tensile strength can be attributed to the weaker bond between the aggregates and cement paste and to the weakness of the polystyrene beads in tension.

Based on the polystyrene/cement ratios used in the study, the tensile strength of Polystyrene-light weight concrete, represented by its modulus of rupture, ranges from $0.16\sqrt{f_c}$ to $0.26\sqrt{f_c}$.

4-3 Actual and theoretical density:

From Table 13, and Figure 31, it is shown that the theoretical density is about 80% of the actual density.

5- Summary of mix design procedure:

1-Multiply target compressive strength by 0.80, since the computed density is about 80 % of the actual density.

2-Use the following table to select a suitable aggregate content.

Table 14: Compressive strength vs. density

AC	Density bounds				
	1500-1550	1550-1590	1640-1740	1740-1780	1840-1940
	28-day compressive strength f_c				
500	14.1-14.65	14.65-15.2	-	-	-
750	-	-	15.2.-16.5	16.5-18.1	18.1-19.8
1000	-	-	-	-	

3-Use any one of the suitable Figures from 4 to 6 to evaluate the cement content, for a trial water/cement ratio of 0.45.

4-For the cement content evaluated in step 3, evaluate the water/cement ratio from Figures 1 to

5- Adjust the cement content if the water/cement ratio evaluated in step 4 is different from the ratio assumed in step 3.

6- Compute the polystyrene/cement ratio using the volume method.

7- Using Figures 7 to 10 check whether the polystyrene/cement ratio is equal to that evaluated in the last step.

Example

Design a polystyrene-lightweight concrete mix with a target compressive strength of 20 MPa, and a density of 1750 kg/m^3.

Solution

1- Reduced compressive strength = 0.80 (20) = 16.0 MPa.

2- Using Table 14, select an aggregate content of 750 kg/m3.

3- From Figure 5, and for w/c = 0.45, the cement content = 490 kg/m3.
4-From Figure 2, w/c = 0.45, in agreement with that assumed in step3.
5- No adjustment required.
6- Volume of the polystyrene = 1- [(490/3150) + (750/2660) + (0.45 * 490/1000)] = 0.34
P/C = 0.34 (490/3150) = 2.18
7- From Figure 8, P/C = 2.19, very close to the ratio evaluated in the previous step.

6- Conclusions:

1-The recommended way in preparing polystyrene-lightweight concrete mixes is to mix the polystyrene beads with the aggregate for about two minutes, after that, both cement and water are added, and mixed for about five minutes in order to get a homogeneous mix.
2-Compaction of polystyrene-lightweight concrete is to be about 50 % of normal-weight concrete, to prevent segregation.
3-The recommended curing period is 14 days.
4-The following proportions are recommended for producing homogeneous mixes with compressive strengths ranging from 17 to 25 MPa and densities ranging from 1650 to 1830 kg/m3.

Table 15: Recommended mix proportions

Quantity	Range
Cement Content	440-550 kg/m^3
W/C Ratio	0.40-0.55
Aggregate Content	500-1000 kg/m^3
Polystyrene	20-40 % m^3/m^3

5-The theoretical density is about 80 % of the actual density.
6-The development of strength is shown by the following table:

Table 16: Compressive Strength as % of 28-day Strength

Age	Compressive Strength as % of 28-day Strength
28	100
3	40
7	60
14	90
60	110
90	120

7-Based on the polystyrene/cement ratios used in the study, the tensile strength of polystyrene-lightweight concrete, represented by its modulus of rupture ranges from $0.16\sqrt{f_c}$ to $0.26\sqrt{f_c}$.

8-Using polystyrene-lightweight concrete in structural elements needs further testing regarding bond between the concrete and the reinforcing bars, the required concrete cover, drying shrinkage, and permeability.

7- Acknowledgement

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