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Flexural Behaviour of Polymer Modified Reinforced Concrete Beams

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Abstract

This research include the study of Structural Behaviour of Polymer Modified Reinforced Concrete Beams with Styrene Butadiene Rubber (SBR) polymer. Two series of concrete mixtures were used; the first was with moderate compressive strength (level I) and the other with compressive strength higher than the former (level II). Two reference mixes were made also for comparative purposes.

This study includes compressive and flexural tests for concrete which was used in this research. The results prove that, polymer modified concrete has compressive and flexural strengths more than reference mixes.

Eight beams are moulded of (95X200X1600mm) dimension with different steel reinforcement ratio (ρ). Load-deflection relationships of beams made of polymer modified concretes and references concretes were established. The moment at mid-span with deflection and moment-curvature relationships were established too.

The effects of steel reinforcement ratio (ρ) and (ρ/ρ_{max}) on the displacement ductility of reinforced concrete beams were concluded.

The PMC beams have a stiffer response in terms of structural behaviour, more ductility and lower cracking deflection than those made by reference concretes and that refer to good role of styrene Butadiene Rubber (SBR) polymer on the properties and behaviour of reinforced concrete beams.

الخلاصـــــــــة

يتضمن هذا البحث دراسة السلوك الإنشائي للعتبات الخرسانية المطورة ببوليمر الـ Styrene Butadiene Rubber (SBR) . تم انتاج سلسلتين من الخرسانة المطورة بالبوليمر إحداهما المستوى الأول متوسطة مقاومة الانضغاط والأخرى المستوى الثاني ذات مقاومة انضغاط أعلى من الأولى كما تم إنتاج خلطتين خرسانيتين مرجعيتين لأغراض المقارنة.

تضمنت الدراسة إجراء فحوصات مقاومة الانضغاط والانثناء للخرسانة موضوع البحث. أثبتت نتائج الفحوصات أن الخلطات الحاوية على البوليمر كانت ذا مقاومة إنضغاط وانثناء أعلى من الخلطات المرجعية.

تم صب ثمانية عتبات خرسانية مسلحة بنسب تسليح مختلفة وبأبعاد (٩٥×٢٠٠×١٦٠٠ ملم) لفحوصات السلوك الإنشائي وبنسب تسليح مختلفة. تم فحص تلك العتبات للانثناء ومن ثم إيجاد علاقات (الحمل-الأود) لهذه العتبات. كما وتم إيجاد العلاقة ما بين العزم في منتصف العتبات مع الأود وعلاقة العزم-الانحناء لجميع العتبات.

إضافة إلى ما تم ذكره تمت دراسة تأثير نسبة حديد التسليح (ρ) ونسبة نسبة حديد التسليح/ نسبة حديد التسليح العظمى (ρ/ρ_{max}) على مطيلية العتبات الخرسانية المسلحة.

لقد أظهرت العتبات الخرسانية المسلحة والمطورة بالبوليمر تصرفاً أكثر صلابة ،أكثر مطيلية واقل أود من مثيلاتها المصنعة بالخرسانات المرجعية مما يدل على تأثير بوليمر الستايرين بيوتادين ربر (SBR) المهم في تحسين خواص وسلوك العتبات الخرسانية المسلحة والمطورة بالبوليمر.

1. Introduction

Developing Countries are trying their best to achieve rapid progress in the fields of industry and housing. Progress involves large-scale construction activities. Cement concrete; hitherto has been one of the important materials of construction, in spite of its many drawbacks. The newly developed "Polymer Concrete" possessing many superior properties over conventional cement concrete, renders itself as one of the most versatile construction materials. Polymer concrete in particular, is highly suitable in case of pre-fabricated building industry, irrigation structures, marine structures, nuclear power production and desalination plants [1].

The concept of polymer modification for cement mortar and concrete is not so new, as in 1923 the first patent of the concept had already been issued to Cresson [2]. This patent refers to paving materials with natural rubber latexes, and cement was used as filler. The first patent with the present concept of polymer modification was published by Lefebure [3] in 1924. Since then, considerable research and development of polymer modification for cement, mortar and concrete have been conducted in various countries for 70 years or more. As a result, many effective polymer modification systems for cement mortar and concrete have been developed, and currently are used in various applications in the construction industry.

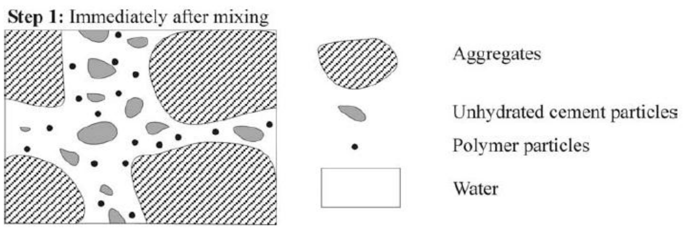
1-1 Polymer Portland Cement Concrete (PPCC)

ACI Manual of Concrete Practice Part 5-1990 [4] defines Polymer Portland Cement Concrete (PPCC) mixtures as normal Portland Cement Concrete to which a water soluble or emulsified polymer has been added during the mixing process. As the concrete cures, hardening of polymer also occurs, forming a continuous matrix of polymer throughout the concrete.

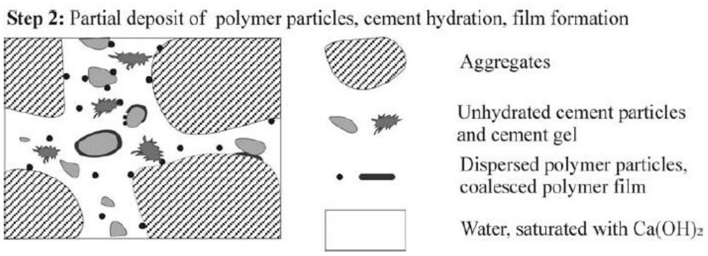
1-2 Principles of Polymer Modification

Although polymer-based admixtures in any form such as polymer latexes, water-soluble polymers and liquid polymers are used in cementitious composites such as mortar and concrete. It is very important that both cement hydration and polymer film formation (coalescence of polymer particles and the polymerization of resins) proceeds well to yield a monolithic matrix phase with network structure in which the cement hydrate phase and polymer phase interpenetrate. In polymer-modified mortar and concrete structures, aggregates are bound by such co-matrix phase, resulting in superior properties compared with conventional cementitious composite [5].

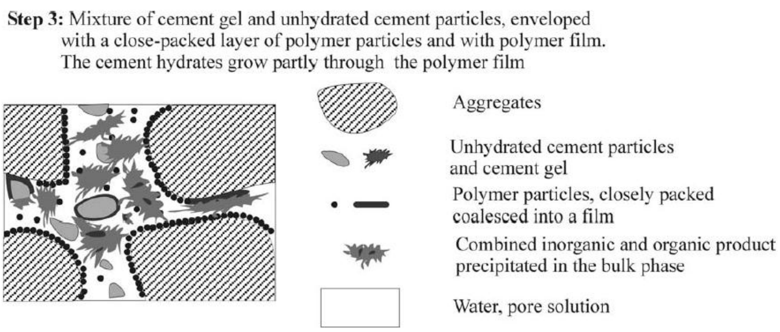
Polymer latex modification of cement mortar and concrete is governed by both cement hydration and polymer film formation. The cement hydration process generally precedes the polymer film formation process by the coalescence of polymer particles in polymer latexes [5,6]. In due course both cement hydration and polymer film formation processes form a co-matrix phase. The co-matrix phase is generally formed according to the simplified model given by Ohama [5], and integrated model by A. Beeldens, et. al. [7], shown in **Fig.(1)**.



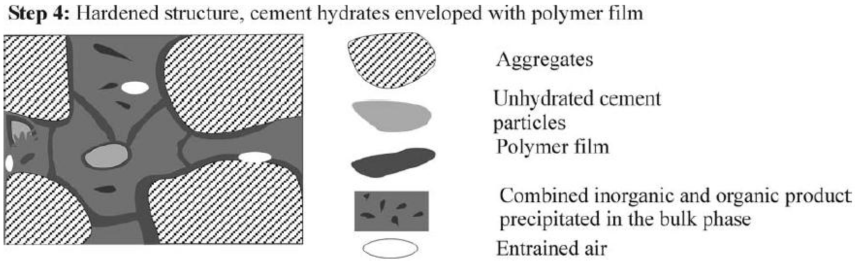
(a) Immediately after mixing



(b) Partial deposit of polymer particles, cement hydration, film formation



(c) Cement hydration proceeds, polymer film formation starts on specific spots



(d) Cement hydration continuous, the polymer particles coalesce into a continuous film

Figure (1) Integrated model of structure formation [7]

1-3 Styrene Butadiene Rubber (SBR) Polymer Modified Concrete

SBR Polymer is the most widely used in concrete. **Figure (2)**, shows the chemical structure of Styrene butadiene Rubber latexes. Co-polymers of butidine with styrene (styrene-butadine rubber (SBR)), are a group of large-volume synthetic rubbers [8]. High adhesion occurs between the polymer films that form and cement hydrates. This action gives less strain compared to ordinary concrete and improves the properties of concrete such as flexural and compressive strength and gives also a higher durability [3].

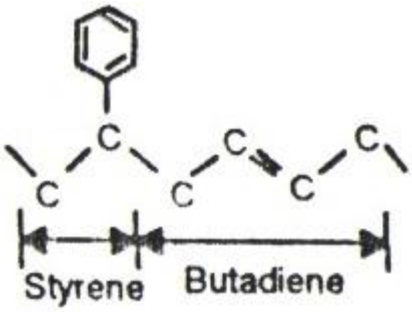


Figure (2) Chemical structures of SBR polymer latexes [8]

1-4 Structural Behaviour of Polymer Modified Concrete Members

Al-Hadithi [9] studied the behaviour of reinforced no-fines polymer modified concrete beams. Two groups of beams were tested. The first group was made of (1:5) (cement:aggregate) with (P:C) ratio equal to (10%) and the second made of (1:6) (cement:aggregate) with (P:C) ratio equal to (10%). Two steel reinforcement ratios were used for each group and they were (ρ=0.0057) and (ρ=0.0129).

The beams with greater compressive strength (fcu=17.6 MPa) ((1:5) (cement:aggregate) with (P:C) ratio equal to (10%)) had a rigidity more than the beams with lower compressive strength (fcu=14.2 MPa) ((1:6) (cement :aggregate) with (P:C) ratio equal to (10%)).

The addition of SBR polymer led to improvement in the behaviour of no-fines concrete beams and this behaviour is identical to that of normal concrete beams.

Al-Numan and Hassan [10] studied the flexural behaviour strength of polymer modified and Fiber-Reinforced polymer modified concrete slabs.

Four test slab groups (450X450X30mm) were used, each of which consisted of three slab specimens identical in size but different in constituent's properties, the slabs are simply supported along four edges. Panels of plain polymer concrete (using 5% of styrene-butadine rubber (SBR)), plain polymer concrete with (1%) superplastcizer, and (1%) by volume fiber reinforced polymer concrete were used in addition to normal reference concrete panels.

Deflections were recorded and cracks were observed. The effect of SBR polymer with and without the inclusion of (1%) by volume steel fibers on the response of panels was studied. The results indicated significant effects of polymer inclusion with and without inclusion of steel fibers on the behaviour of panels.

2. Experimental Work

2-1 Materials

2-1-1 Cement

Sulphate resisting Portland cement from Al-Qa'em factory, conforming to Iraqi standard [11], was used throughout the investigation. The chemical composition and physical properties are given in **Table (1)**. It was tested at National Center for Construction Laboratories and Researches.

Table (1-a) Chemical properties of sulphate resisting cement

Compound	Percentage by weight	Limits of Iraqi specification No.5/1999
SiO2	21.83	-
Al2O3	3.7	-
Fe2O3	5	-
CaO	60.72	-
MgO	2.2	≤5%
SO3	2.18	≤ 2.5%
L.O.I	2	≤ 4%
C3S	42.84	-
C2S	30.36	-
C3A	2.56	≤ 3.5
C4AF	15.41	-
I.R	1	≤ 1.5
L.S.F	0.85	0.66-1

Table (1-b) Physical properties of sulphate resisting cement (with fineness 365 m2/kg)

Physical properties	Test result	Limits of Iraqi specification No.5/1984
Fieness (m^2/kg)	365	
Setting time:		
Initial (minutes)	129	≥ 45
Final (hours)	3:47	≤10
Compressive strength(N/mm^2)		
3day	17.4	≥15
7day	25.2	≥23

2-1-2 Fine Aggregate

Natural sand from Al-Habaniya region in Al-Anbar Governorate was used in production of concrete specimens used in this study. Results of sieve analysis of this sand are shown in **Table (2)**. It is shown that the sand confirms to Limits to the requirements of the Iraqi specification (IOS) No. 45-99 [12], zone (2).

Specific gravity and absorption of the used sand were calculated according to ASTM-Designation: C 128-88 [13] and they were equal to 2.68 and 3% respectively. The sulfate content was equal to 0.35%.

Table (2) Sieve analysis results of the sand used

Sieve Size	Accumulated percentage passing	Limits of Iraqi Specifications No. 45:1999 [10], Zone 2
4.75mm	100	90-100
2.36mm	96.3	75-100
1.18mm	77.6	55-90
600micron	50	35-59
300micron	32	8-30
150micron	12.5	0-10

2-1-3 Coarse Aggregate

Graded uncrushed gravel from Al-Jarayishi region in Al-Anbar Governorate was used for all concrete mixes in this study. The aggregates were conforming to the requirements of the Iraqi specification (IOS) No. 45-99 [12].

As shown in **Table (3)** which gives the sieve analysis results of the coarse aggregate. Specific gravity was equal to 2.79 and sulfate content was equal to 0.075%.

Table (3) Sieve analysis results of the gravel used

Sieve Size	Accumulated percentage of passing %	Limits of Iraqi Specifications No. 45:1999 [10]
14.0	100	100
10.0	94.8	85-100
5.0	9.3	0-25
2.36	0	0-5

2-1-4 Mixing Water

Ordinary tap water was used in this work for all concrete mixes and curing of specimens.

2-1-5 Polymer

Styrene butadiene rubber (SBR) is used as polymer modifier in this study. Styrene butadiene, an elastomeric polymer, is the copolymerized product of two monomers, styrene and butadiene. Latex is typically included in concrete in the form of a colloidal suspension polymer in water. This polymer is usually a milky-white fluid. The Gulf International Chemicals Company, Oman, manufactured this polymer and the typical properties of SBR polymer is shown in **Table (4)**. The polymer (SBR) was used as a ratio by weight of cement of 3%, 5% and 10%.

Table (4) Typical properties of Styrene Butadiene Rubber (SBR) polymer

No	Properties	Description
1	Appearance	White emulsion
2	Specific Gravity	1.03 ± 0.02@ 25°c
3	pH Value	9±2
4	Freeze/Thaw Resistance	Excellent
5	Chloride Content	Nil
6	Flammability	Non-flammable
7	Compatibility	Can be used with all types of Portland cement

*** *1(volume) of SBR mixing with (1-2) (volume) of water to produce a liquid polymer which is added to concrete mix.***

2-1-6 Reinforcement

All reinforcing steel bars were deformed except 6mm bars. Diameters of bars were (6,10,12) mm. **Table (5)** gives the results of bars tests.

Table (5) Properties of reinforcement

Nominal Diameter (mm)	Fy (Mpa)	Fu (Mpa)	Elongation (%)
6	376	512	15
10	460	563	10.5
12	458	568	12.5

*** *The Tests were made by (NCCL)***

2-1-7 Reinforced Concrete Beam Specimens for Structural Behaviour

Specimen details are shown in **Fig.(3)**. All beams were (95mm) wide and (200mm) deep and spans (1600mm). The average effective depth was (188mm). The reinforcing steel bars were cut to a desired length, and a 180-deg hook was formed at the end of each bar dimensioned according to Section 7.1 and 7.2 of ACI 318-02 [14]. 6 mm smooth bar stirrups were provided over the hook length according to Section 12.5.4 of ACI 318-02 [14]. The details of the flexural beam specimens are shown in **Table (6)**.

Three levels of steel reinforcement ratios were used. The approximately minimum ratio (ρ=0.00313) and maximum ratio (ρ=0.019) according to ACI 318-02 [14], in addition to a third level in between (ρ=0.0107) were used in order to investigate the behaviour of PMC beams covering the code allowable levels of reinforcement. Cubes of (100X100X100) mm for compressive strength were used with beam specimens to determine the compressive strength of these beams.

2-1-8 Preparation of Concrete Specimens

A mechanical mixer of the capacity (0.07) m3 operated by electrical power was used .First of all aggregates and cement were added before adding the polymer and dry mixing were continued until the dry mix became homogenous, then the polymer was added until all particles are fully coated with polymer and finally water were added and mixing continues until uniform mix is obtained. This procedure is similar to the method used by Ohama [5].

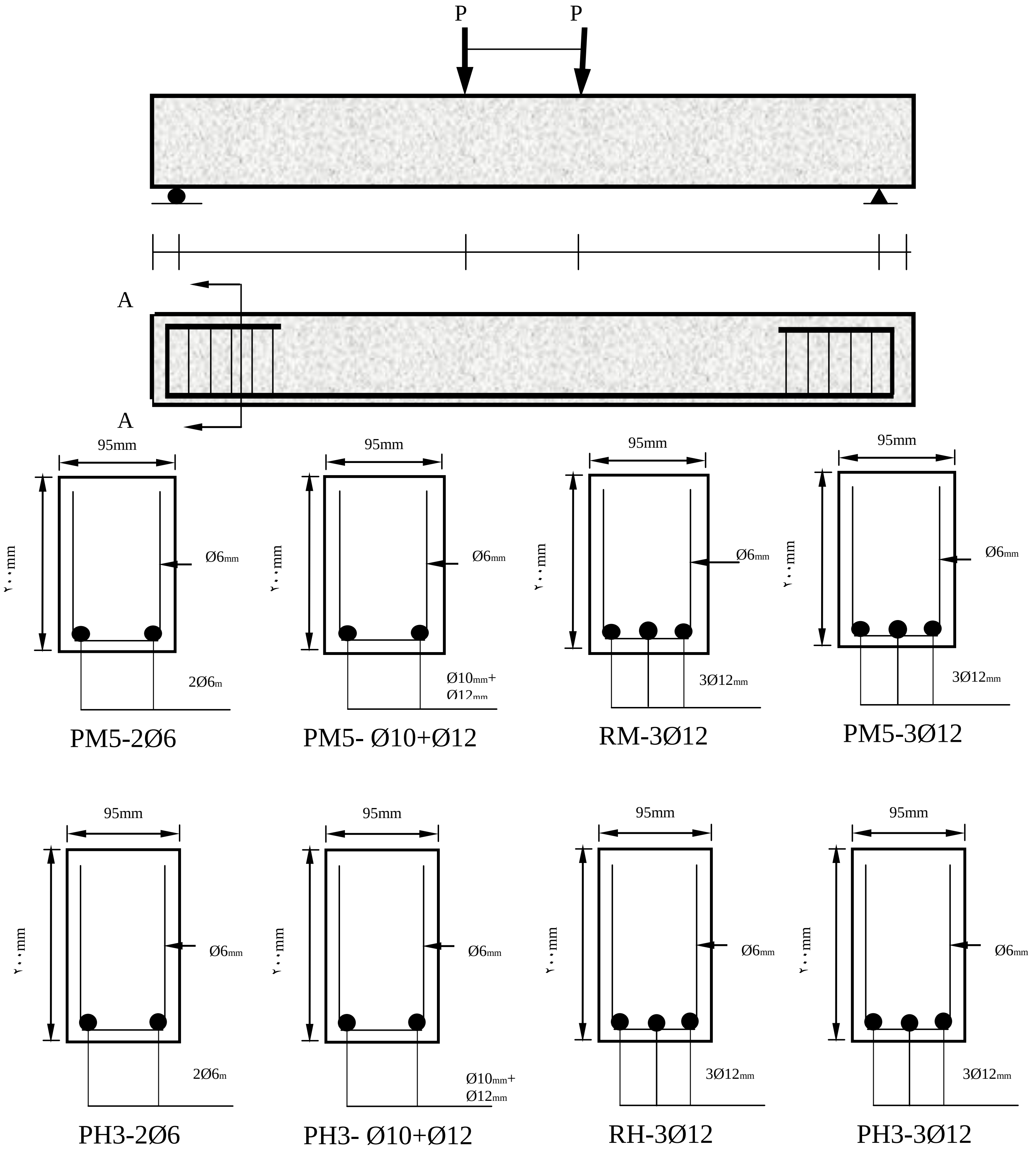


Figure (3) Loading and reinforced beam specimens details

Table (6) Details of the flexural beam specimens
a) Concrete level I with moderate compressive strength

Symbol	b (mm)	h (mm)	d (mm)	(P/C) %	Reinforcement		
					Number of 10mm bars	Area of reinforcement (mm2)	ρ
RM-3Ø12	95	200	187	-	3Ø12	339	0.019
PM5-2Ø6	95	200	190	5	2Ø6	56	0.00313
PM5-Ø10+Ø12	95	200	188	5	Ø10+Ø12	191	0.0107
PM5-3Ø12	95	200	187	5	3Ø12	339	0.019

b) Concrete level II with higher compressive strength

Symbol	b (mm)	h (mm)	d (mm)	(P/C) %	Reinforcement		
					Number of 10mm bars	Area of reinforcement (mm2)	ρ
RH-3Ø12	95	200	187	-	3Ø12	339	0.019
PH3-2Ø6	95	200	190	5	2Ø6	56	0.00313
PH3-Ø10+Ø12	95	200	188	5	Ø10+Ø12	191	0.0107
PH3-3Ø12	95	200	187	5	3Ø12	339	0.019

2-1-9 Mix Proportions

Two groups of mixes were used in this research. **Table (7)** shows the mix proportions of materials used in this work.

Table (7) Mix proportions of materials used in this work for making one cubic meter of concrete
a) Concrete level I with moderate compressive strength

Symbol	Cement (kg)	Sand (kg)	Gravel (kg)	Water Liter	Polymer (liter)			W/C %	(P+W)/C %
					Mixture of polymer	Liquid Polymer (33%)	Water (66.67%)		
RM*	340	515	1385	183.92	-	-	-	0.54	-
PM5	330.8	501.16	1347.6	162	16.54	5.52	11.02	0.49	0.54

b) Concrete level II with higher compressive strength

Symbol	Cement (kg)	Sand (kg)	Gravel (kg)	Water Liter	Polymer (liter)			W/C %	(P+W)/C %
					Mixture of polymer	Liquid Polymer (33%)	Water (66.67%)		
RH*	550	656.8	985	214.5	-	-	-	0.39	-
PH3	538	642.6	963.6	191.39	16.15	6.12	11.124	0.36	0.39

****Water curing (14) days, whereas all the other mixes were (2) days water curing.***

For symbols the letters which were used mean as below:

R: Reference
M: Moderate compressive strength
P: Polymer
Number (like 3): Polymer content as a percentage by weight of cement content
H: Higher compressive strength

2-1-10 Casting, Compacting and Curing

The moulds were lightly coated with mineral oil before use, according to ASTM C192-88 [15], concrete casting was carried out in three layers. Each layer was compacted by using a vibrating table until no air bubbles emerged from the surface of concrete and the concrete is levelled off smoothly to the top of moulds. Then the specimens were kept in the laboratory for about (24) hrs. After that the specimens remoulded carefully and for two days immersed in water for polymer concrete specimens, whereas the control specimens immersed in water for (14) days. For the beam specimens the vibrating was done internally using immersing vibrator.

2-1-11 Compressive Strength Test

Compressive strength was determined using (100X100X100) mm cubes according to B.S.1881 part 116 [16] .ELE machine with a capacity of (1000) kN was used for that test. The average compressive strength of three cubes was recorded for 28 days age.

2-1-12 Flexural Strength Test

(100X100X500)mm Concrete Prisms were prepared according to ASTM C192-88(15). Two point load test was carried out according to ASTM C78-94 [17] using ELE (50)kN capacity machine. Average modulus of rupture of two prisms was recorded for 28 days age.

2-1-13 Load Measurement

A flexural machine with a (3000)kN hydraulic jack is used for testing the beam specimens at two point load arrangement over simply supported span of (1440) mm as shown in **Fig.(3)** and **Plate (1)**.

Plate (1) Set-Up of beam specimen test

3. Results and Discussion

The results of the tests of reinforced concrete beams are presented. Effects of concrete strength, reinforcement ratio on deflection, moment-deflection relationship, member's ductility, crack patterns and moment-curvature relationship are investigated and discussed.

The details cover the polymer modified concrete beams with moderate compressive strength denoted by PM5 mix and the polymer modified concrete beams with higher mechanical properties denoted by PH3. These beams were tested at (28) day age. The details of all beams are mentioned in section (2-1-7).

3-1 Concrete Compressive Strength "fcu"

The compressive strength test results obtained for the average of three 100 mm cubes for each mix made in this study are given in **Table (8)**. It can be noticed that the compressive strength of polymer modified beams is higher than the compressive strength of beams made from the reference mixes. That increase in compressive strength might be due to three facts. The first is that, PMC had less W/C ratios, which gave higher strengths. The second is that, the use of SBR polymer leads to form a continuous three-dimensional network of polymer molecules throughout concrete which increases the binder system due to good bond characteristics of the polymer SBR. The last is the partial filling of pores with polymer which reduces the porosity, and hence increases the strength [5,18].

Table (8) Properties of Polymer Concrete in Test Beams

Mix No.	Concrete Level	Polymer:cement Ratio %	Compressive Strength "fcu" (At 28 days) MPa	Flexural Strength "fr" (At 28 days) MPa
Rm	I	0	29	3.67
PM5		5	36	3.85
RH	II	0	35	3.78
PH3		3	43	4.14

3-2 Flexural Strength "fr"

The results of flexural strength (modulus of rupture) at 28 days age are given in **Table (8)**. It is evident that with an increase in (P:C) ratio, flexural strength for concrete level II with higher compressive strength will be increased for the same reasons mentioned for the compressive strength. For concrete mixes of concrete level I with moderate compressive strength there is increase in flexural strength at (28) days compared with reference Mix. (RM).

3-3 Load-Deflection Behaviour

Table (9) shows properties and maximum load and deflections of the tested beams. **Figures (4-6)** show load-deflection at mid spans for the eight beams with different reinforcement ratios.

In the pre-cracking stage, the deflection increases linearly with an increase in load. This is expected since the strains in the steel and concrete are relatively small and both materials are in the elastic portion of their respective response. The beam with higher value of reinforcement ratio (ρ) has stiffer responses to loading in general due to a higher moment of inertia as shown in **Figs.(4-6)**.

For polymer modified concrete level I with moderate compressive strength beams, initial cracking was observed at loads ranging from 34.28% of ultimate load for (PM5-3∅12) beam to 43.24% for (PM5-2∅6) beam. The initial cracking for polymer modified concrete level II with higher compressive strength was observed at loads ranging from 25% of ultimate load for (RH-3∅12) beam to 42.43% for (PH5-2∅6) beam.

There is change of slope in the load-deflection curve in the post cracking stage due to the reduction in the effective moment of inertia.

Table (9) Properties, deflection and ductility of reinforced concrete beams

Beam	ρ	ρ_{max}	ρ / ρ_{max}	Max. Load (kN)	Max. defl. (mm)	Max. Moment (kN.m)	Δy (mm)	Ductility μ_d
RM-3Ø12	0.019	0.021	0.905	69	4.46	27.44	2.243	1.988
PM5-2Ø6	0.00313	0.0279	0.112	37	7.6	14.8	1.353	5.617
PM5-Ø10+Ø12	0.0107	0.0249	0.431	66	5.94	26.255	1.31	4.53
PM5-3Ø12	0.019	0.0249	0.763	70	0.95	27.835	0.2438	3.9
RH-3Ø12	0.019	0.0251	0.757	73	1.61	28.18	0.994	1.62
PH3-2Ø6	0.00313	0.0331	0.0946	38	2.8	15.195	0.333	8.58
PH3-Ø10+Ø12	0.0107	0.027	0.398	76	5.47	30.205	0.9	6.08
PH3-3Ø12	0.019	0.027	0.704	80	0.574	31.785	0.10	5.74

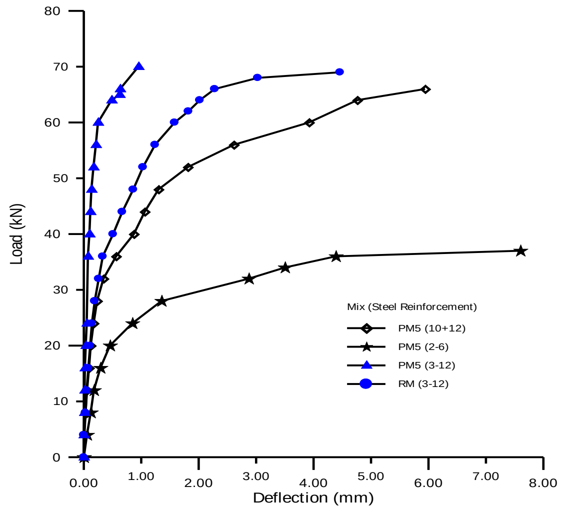


Figure (4) Load-Deflection curves at mid-span for polymer modified concrete level I with moderate compressive strength beams

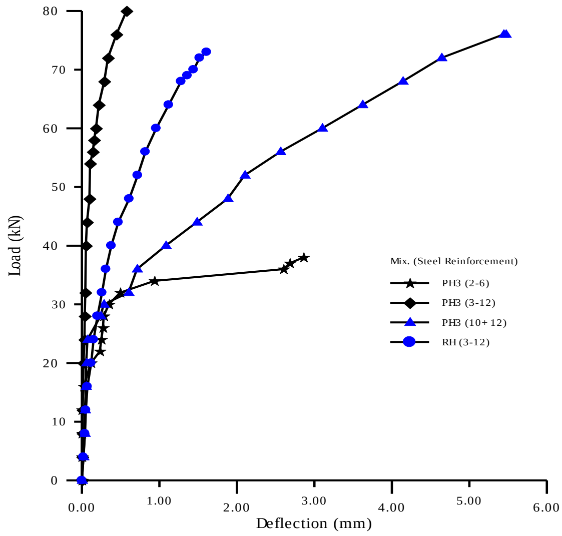


Figure (5) Load-Deflection curves at mid-span for polymer modified concrete level II with higher compressive strength beams

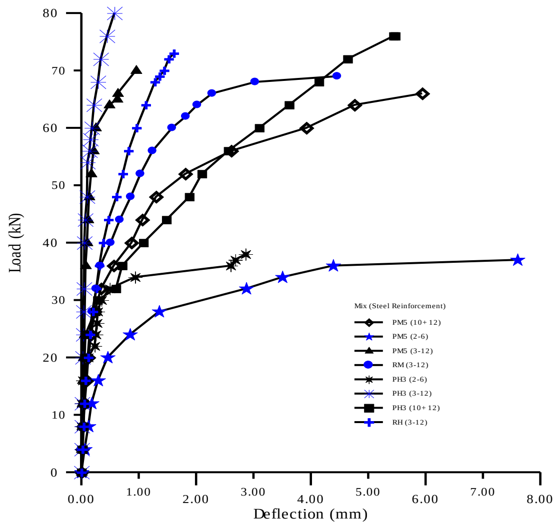


Figure (6) Load-Deflection curves at mid-span for polymer modified concrete with moderate and higher compressive strength beams

3-4 Effect of Concrete Compressive Strength

Figure (4), **Fig.(5)** and **Fig.(6)** show the comparison of load-deflection curves of all beams. The beams with higher reinforcement amount have less deflection than the other beams. For beams containing polymer with the same reinforcement amount but different concrete strength values, the beam which has higher strength values suffers less deflection than a similar beam with lower strength value, at the same load up to failure.

The ultimate loads of polymer modified beams are higher than those of reference beams of the same reinforcement amount. The first crack deflections are also lower for polymer modified beams than those of reference beams.

For polymer modified concrete level II with higher compressive strength beams, the beam (RH-3Ø12) has an ultimate load less than the beam (PH3-3Ø12), which had the same steel reinforcement. The former has a 1st crack deflection equal to (Δcr=0.032 mm) whereas the latter has a 1st crack deflection equal to (Δcr =0.159 mm). SBR polymer addition has an effect on decreasing of the deflection in crack stage. The SBR network probably plays a role in increasing the rigidity of beams.

In comparing beams (PM5-2Ø6, fcu=36 MPa, fr=3.85MPa, Max. defl.=7.6mm) and the other beam with same reinforcement, but with higher in strength (PH3-2Ø6, fcu=43 MPa, fr=4.14 MPa, Max. defl.=2.8mm) ,it can be seen that the effect of SBR polymer is clear in increasing strength and rigidity and then decreasing deflection .

The values of cracking moment (Mcr) and 1st crack deflection (Δcr) of all beams are listed in **Table (10)**.

Table (10) Deflection of creaking and moment of cracking of reinforced concrete beams

Beam	ρ	Δ crack (mm)	ΔMax (mm)	M crack (kN.m)	M max (kN.m)	ΔMax/Δ crack	Mmax/Mcrack
RM-3Ø12	0.019	1.67	4.46	10.824	27.44	2.67	2.535
PM5-2Ø6	0.00313	0.176	7.6	6.5	14.8	43.043	2.27
PM5-Ø10+Ø12	0.0107	0.138	5.94	9.27	26.255	44.23	2.832
PM5-3Ø12	0.019	0.048	0.95	9.70	27.83	19.79	2.88
RH-3Ø12	0.019	0.148	1.61	9.65	29.01	10.88	3.00
PH3-2Ø6	0.00313	0.159	2.8	9.66	15.19	57.73	1.57
PH3-Ø10+Ø12	0.0107	0.148	5.47	9.027	30.2	34.4	3.33
PH3-3Ø12	0.019	0.032	0.574	9.467	31.785	17.938	3.934

3-5 Effect of the Amount of Tension Reinforcement

Figure (6) shows the difference between the beam (PM5-3Ø12, Max. defl.=0.95 mm) and beam (PM5-2Ø6, Max. defl.=7.6 mm), which has the same concrete compressive strength, but different amounts of reinforcement ratio. An increase in load capacity due to the increase in reinforcement ratio can be shown.

3-6 Moment-Deflection Relationship

Figure (7) shows the moment-deflection curves for eight beams. In pre-cracking stage, deflection increases linearly with moment. The cracking moment increases with the increase in concrete compressive strength and longitudinal reinforcement amount.

For example, beam (PH3-3Ø12, fcu=43 MPa) with M/Mcr about 3.934 yields Δ/Δcr of about 17.938, whereas beam (PM5-3Ø12, fcu=36 MPa) with M/Mcr about 2.88 yields Δ/Δcr of about 19.79. This means that deflection is reduced with an increase in compressive strength of concrete. But M/Mcr is reduced with the reduction in longitudinal reinforcement amount due to the reduction in beam capacity.

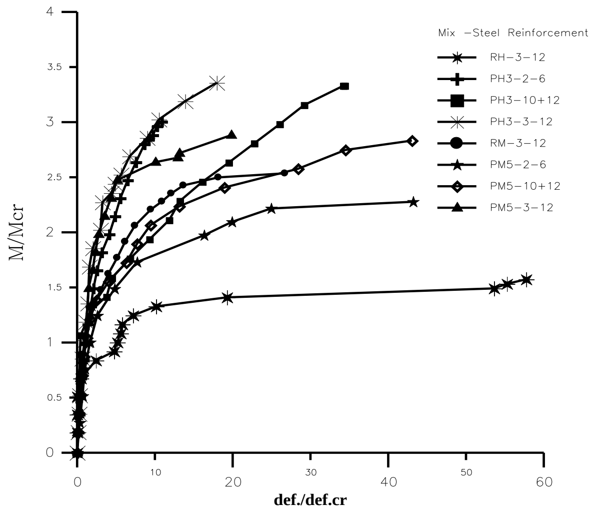


Figure (٧) Moment versus mid-span deflection relationship for all beams

Cracking patterns of the tested beams at failure are shown in **Plate (2)** and **Plate (3)**. Cracking in the flexural span consists of predominately of vertical cracks. This is expected since the concrete, which cracks perpendicular to the direction of maximum principal stress, is subjected to longitudinal tensile stresses that are induced by the pure moment.

For beams (RM-3Ø12, ρ=0.019), (PM5-3Ø12, ρ=0.019), (RH-3Ø12, ρ=0.019), (PH3-3Ø12, ρ=0.019), (PM5-Ø10+ Ø 12, ρ=0.0107) and (PH3-Ø10+ Ø 12, ρ=0.0107) initial crack propagation outside the pure moment region is similar to flexural cracking. However, inclined cracking then, begins due to the presence of increasing shear stresses as the load is increased. The joining of the inclined crack to a flexural crack results in a flexural shear crack. That means failure in these beams is flexural-shear failure. Failure occurs to due to the propagation of these cracks toward the vicinity of the point load at the compressive face of the beam.

RM-3Ø12

PM5-3Ø12

PM5-2Ø6

PM5- Ø 10+Ø12

Plate (2) Failure mode of reinforced concrete beams made by polymer modified concrete with moderate compressive strength

RH-3Ø12

PH3-3Ø12

PH3-2Ø6

PH3- Ø10+Ø12

Plate (3) Failure mode of reinforced concrete beams made by polymer modified concrete with higher compressive strength

For the beams with lower reinforcement in this study, (PM5-2Ø6, ρ=0.00313) and (PH3-2Ø6, ρ=0.00313), the crack propagation is inside the pure moment and it is similar to flexural cracking. These flexural cracks grow upward with an increase of the applied load until failure. The failure in these beams is mainly flexural failure.

Number of cracks and length of crack growth in beams made by polymer modified concrete level I with moderate compressive strength are greater than that of beams made by polymer modified concrete level II with higher compressive strength clearly shown in the **Plate (2)** and **Plate (3)**. In general cracks of beams made of polymer modified concrete are finer in distribution and shorter in length than those of references mix.

3-7 Ductility

Member ductility is best expressed in terms of deflection. Deflection-ductility is defined as the ratio of deflection at ultimate to the deflection at the yielding of the tensile steel. Ultimate stage is defined as the stage beyond which it was felt during the testing that the beam would not be able to sustain additional deformation at the same load intensity [19].

Results of ductility index (μd) are listed in **Table (10)**. From these results it can be seen that (μd) increases with the decrease in tensile reinforcement ratio (ρ) as shown in **Fig.(8)**, for example for beams (PH3-3Ø12, ρ=0.019) and (PH3-2Ø6, ρ=0.00313) the ductility index (μd) ranged (5.74 and 8.58).

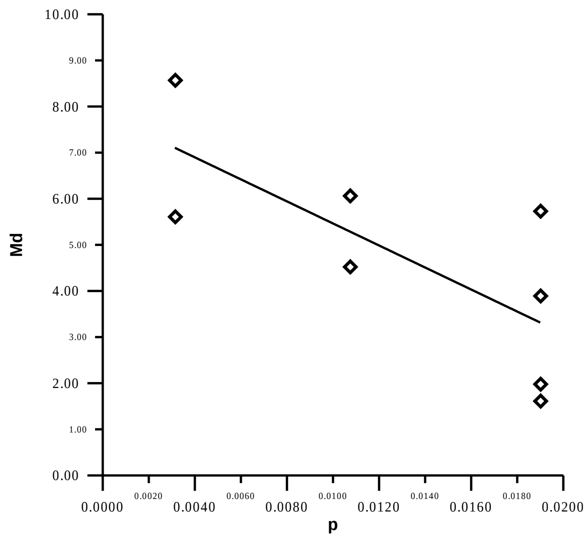


Figure (٨) Effect of reinforcement ratio (ρ) on displacement ductility

As shown in **Fig.(9)**, ductility index (μd) decreases with the increasing in (ρ/ρmax) ratio. From **Table (9)** and the figure mentioned above, it can be seen that the beams made of polymer modified concrete level II with higher compressive strength have a ductility index (μd) greater than that of the beams made from polymer modified concrete level I with moderate compressive strength. That might be due to the higher content of SBR polymer in the former. The results in **Fig.(8)** show that, for polymer modified concrete level II with higher compressive strength represented by beams made from PH3 mix, the (μd) decreases with (ρ/ρmax). The (μd) values vary from (8.58) for (PH3-2ø6) beam which its (ρ/ρmax) equal to (0.0946) to (5.617) for (PH3-3ø12) beam which is (ρ/ρmax) equal to (0.704).

For polymer modified concrete level I with moderate compressive strength represented by beams made from PM5 mix, the (μd) decreases with (ρ/ρmax) also. The (μd) values vary from (5.617) for (PM5-2ø6) beam, which is (ρ/ρmax) equal to (0.112) to (3.9) for (PM5-3ø12) beam, which is (ρ/ρmax) equal to (0.763). For the beams made from Polymer modified concrete level I with moderate compressive strength, the value of (μd) appears to be less sensitive to change in (ρ/ρmax).

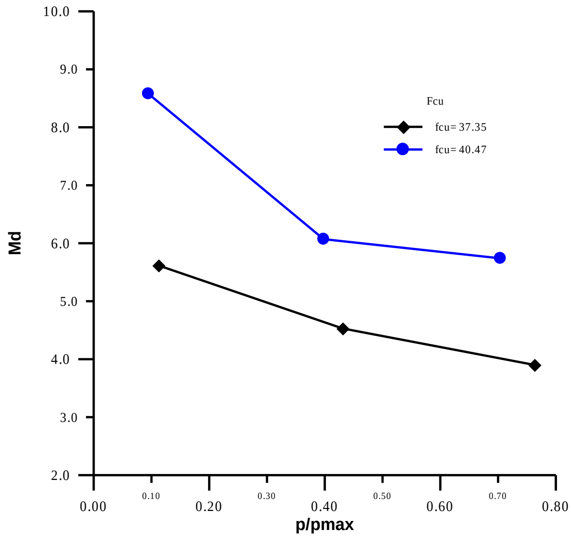


Figure (٩) Effect of reinforcement ratio (ρ/ρmax) on displacement ductility

3-8 Moment-Curvature Relationship

Figure (10) represents the moment-curvature relationship for eight beams. Curvature of beams is calculated by using the equation below [20].

$$\delta = l^2/96\,(\lambda_{e1} + 10\,\lambda_c + \lambda_{e2}) \quad \text{.......... (1)}$$

where:

δ: deflection of beam at center of the span
l: length of span.
λ: curvature of the beam
e1 and e2: are end regions.
c: center region

The curvature varies along the length of beam because of fluctuation of the neutral axis depth. In ultimate stage, there is an increase in curvature value due to an increase in strain value at extreme compressive fiber with the increase in concrete compressive strength for beam PH3-3Ø12 and PM5-2Ø6 the curvature is (2.6574×10^{-6} and 3.52×10^{-5} 1/mm).

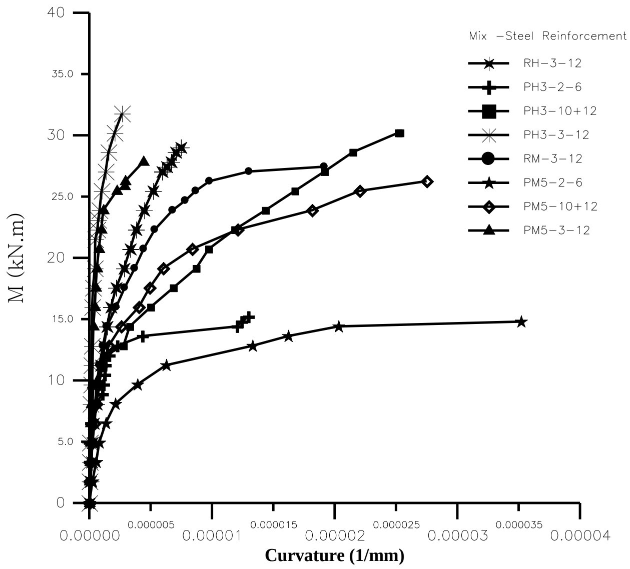


Figure (10) Moment-curvature relationship for (RM-3Ø12) beam

4. Conclusions

Based on the research works, the following conclusions can be drawn:

- The beam with the higher steel content and/or higher compressive strength has a stiffer response in terms of load-deflection behaviour, and the beams made from polymer modified concrete have a stiffer response than those made of references mixes.
- The polymer modified concrete beams yield high M/Mcr values that range between (1.57 to 3.934). This may be attributed to the high ability to carry the load at post-cracking stage due to the stiffness in polymer modified concrete.
- There is a decrease in curvature with an increase in reinforcement ratio. On the other hand, there is a significant decrease in curvature with an increase in concrete compressive strength. The maximum curvature values range between ($2.6574X10^{-6}$ and $3.52 X 10^{-5}$ 1/mm).

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