INFLUENCE OF CURING REGIMES ON THE COMPRESSIVE STRENGTH OF THE REACTIVE POWDER CONCRETE (RPC) USED IN RIGID PAVEMENTS [+]

تأثير طرق الإنضاج على مقاومة انضغاط الخرسانة الحاوية على مواد ناعمة فعالة (RPC) التي تستخدم في البلاطات الصلدة

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Abstract:

Experimental and analytical works were done in order to study the effect of different curing methods and determine the *best curing method* which characterize the mechanical properties (compressive strength) of Reactive Powder Concrete (RPCs), in order to use it in rigid pavements (Airport Pavements) in Iraq. RPCs specimens were subjected to *five* types of curing regimes, *Modified Curing (C1)*, specimens are immersed in hot water at 60°C for 7 days starting at one day after cast, specimens are then stored at 23°C & 100% RH until testing, *Normal Curing (C2)*, specimens are allowed to remain in a standard environment conditions (23°C & 95% RH) starting at one day after cast until testing, *Delayed Curing (C3)*, specimens are subjected to *Normal Curing (C2)* for 10 days after casting then specimens are subjected to *Steam Curing (C4)* for 48 hours, *Steam Curing (C4),* specimens are subjected to thermal steam treatment for 48 hrs at 90°C & 100% RH starting at one day after cast, specimens are then stored at 23°C & 100% RH until testing, and the *Steam Pressure Curing (C5),* specimens are autoclaved at 120°C & 1.0 MPa for 3 hours starting at one day after cast, specimens are then stored at 23 °C & 100% RH until testing. Test results show that the highest compressive strength were obtained by both the C1 and C3 curing methods. Depending upon mix proportions and age of test, the percentages of increasing in the compressive strength of RPCs specimens with respect to curing types were as follows:

(a) *For mixes without polymers:* C1 recorded (59.03, 14.69, 32.16, and 14.67)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively; and C3 recorded (39.42, 20.70, and 23.38)% higher 28-day compressive strength than (C2, C4, and C5) respectively.

(b) *For mixes with polymers:* C1 recorded (20.99, 5.83, 30.59, and 26.07)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively; and C3 recorded (28.59, 38.78, and 57.34)% higher 28-day compressive strength than (C2, C4, and C5) respectively.

Key words: Curing Regimes, Compressive Strength, (SCMs), Trial Mixes, Rigid Pavements.

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المستخلص:

تم اجراء الفحوصات المختبرية و تحليل نتائجها لغرض دراسة تأثير انــواع الانــضاج (curing methods) علـــى مقاومة الخرسانة الحاوية على مواد ناعمة فعالة (RPC) واختيار افضل طريقة انــضاج لغــرض اســتخدامها فـــي البلاطات الصلبة (مدارج الطائرات) في العراق.

تم تعريض النماذج المختبرية الى خمسة انواع من الانضاج، المعالجة المعدلة [C1]، الانضاج الذي يتضمن غمر النماذج المختبرية في الماء الساخن بدرجة حرارة (60) °م لمدة (7) أيام، المعالجة الاعتيادية [C2]، الانــضاج الذي يتضمن غمر النماذج في الماء بدرجة حرارة (23oC) و رطوبة نــسبية (100%) لحــين فحــصها، المعالجــة المتأخرة [C3]، الانضاج الذي يتضمن تعريض النماذج المختبرية للمعالجة الاعتيادية لمدة (10) أيام ومن ثم تعريض هذه النماذج الى الانضاج بالبخار لمدة (48) ساعة، المعالجة بالبخار [C4]، الانضاج الذي يتضمن تعريض النمــاذج للبخار الحراري بدرجة حرارة (90oC) و رطوبة نسبية (100%) لمدة (48) ساعة، و اخيرا المعالجــة بالبخــار و الضغط [C5]، الانضاج الذي يتضمن معالجة النماذج بالمحمم المائي بدرجة حرارة (120oC) و ضــغط (1.0 MPa) لمدة (3) ساعات.

نتائج الفحوصات اظهرت بأن اعلى القيم لمقاومة الانضغاط لهذا النوع من الخرسانة قد تم الحــصول عليهــا بأتباع كل من طرق الانضاج [C1] و[C3] . واعتمادا على نسب الخلط وعمر الفحص، تبين بأن نسب الزيــادة فـــي مقاومــة الانــضغاط كانــت كمــا يلـــي:

آ- للخلطــات بــدون البــولمرات: [C1] ســجلت مقاومــة انــضغاط بعمــر (28) يــوم اعلـــى بمقــدار (59.03, 14.69, 32.16 & 14.67)% من (C2, C3, C4 & C5) على التوالي; وان [C3] قد سجلت مقاومة انضغاط بعمر (28) يوم اعلى بمقدار (39.42, 20.70 & 23.38)% من (C2, C4 & C5) على التوالي.

ب- للخلطــات بــالبولمرات: [C1] ســجلت مقاومــة انــضغاط بعمــر (28) يــوم اعلـــى بمقــدار (20.99 , 5.83 , 30.59 & 26.07)% من (C2, C3, C4 & C5) على التوالي; وان [C3] قد سجلت مقاومة انضغاط بعمر (28) يوم اعلى بمقدار (28.59 , 38.78 & 57.34)% من (C2, C4 & C5) على التوالي.

الكلمات المفتاحية: طرق انضاج الخرسانة، مقاومة الانــضغاط، (SCMs)، الخلطــات التجريبيــة، البلاطــات الصلبة.

Introduction:

Reactive Powder Concrete (RPC) is the special type of ultra high-strength superplasticized silica fume concrete, often fiber-reinforced, with improved homogeneity because traditional coarse and fine aggregate are replaced by very fine sand with particle size in the of (100 to 600) μm. It is characterized by extremely good physical properties, particularly strength and ductility[1].Curing is the gain of a satisfactory moisture condition and temperature in concrete for a period of time immediately after placing and finishing of concrete so that the desired properties may develop. Curing has a strong influence on the properties of hardened concrete; proper curing will increase durability and strength[2]. In severe cases, the hydration is eventually stopped. When the hydration is stopped, sufficient calcium silicate hydrate (CSH) cannot develop from the reaction of cement compounds and water. Calcium silicate hydrate is the major strength-providing reaction product of cement hydration[3]. Moreover, the drying of concrete surfaces results in shrinkage cracks that may aggravate the durability problems. Therefore, an efficient curing is inevitable to prevent the moisture movement or evaporation of water from concrete surface. It can be accomplished by keeping the concrete element completely saturated or as much saturated as possible until the water-filled spaces are substantially reduced by hydration products. Therefore, a suitable curing method such as water ponding, spraying of water, or covering with wet burlap and plastic sheet is essential in order to produce strong and durable concrete[4,5]. Curing methods included: *ponding and immersion*; *fogging and sprinkling*; *wet coverings*; *impervious paper*; *plastic sheets*; *membrane-forming curing compounds*; *internal moist curing*; *steam curing*; *insulating blankets or covers*; *electrical, oil, microwave, infrared curing, fog room, (60% humidity), room temperature (23^{o}C), ordinary curing (moist curing environment), burning, wrapped curing, dry-air curing, ambient air curing, water curing, and single–atmosphere curing*. For the high-temperature effect test, the specimens were exposed to a 500^{o}C temperature for 2 hours in a muffle furnace and then the compressive strength test was conducted after cooling in laboratory in open air for (24) hours. The majority of specimens were cured in tap water at the specified temperature and ambient pressure. However, some mixes designed for high-temperature curing (i.e. those containing quartz fines to modify the CaO/SiO_2 ratio of the binder) were autoclaved in a steel pressure vessel at 160^{o}C, corresponding to a steam pressure of about 0.5 MPa above atmospheric pressure[6,7]. Some investigators[4] used the following types of curing: (1) *Standard Steam Treatment*, included thermal steam treatment of the specimens for 48 hours at 90^{o}C and 100% relative humidity; (2) *Untreated regime*, wherein allowed the specimens to remain in a standard laboratory environment from demolding until testing; (3) *Tempered Steam*, at lower temperature version of the same steam treatment, it is very similar to the steam treatment, except that the temperature inside the steam chamber was limited to 60^{o}C; (4) *Delayed version*, it is a curing regime wherein the *steam treatment* described above is followed, but it is initiated until the 15th day after casting. Until the 15th day, delayed steam specimens are equivalent to untreated specimens; and (5) *Steam Pressure Curing*, specimens were autoclaved at 217^{o}C/2.0 MPa/2, 3 days. The *ASTM C 684* uses accelerated strength tests to expedite quality control of concrete. Cylinders are tested using one of the <u>*four*</u> accelerated curing procedures: (a) *Warm Water* at 35^{o}C ± 3^{o}C; (b) *Boiling Water*; (c) *Autogenous* (insulated); and (d) *High Temperature* at 150^{o}C ± 3^{o}C. Accelerated strength tests are performed at ages ranging between 5 and 49 hours, depending on the curing procedure used. The accelerated curing is usually costs money. Precast concrete procedures realize that accelerated curing provides cost savings in both time and materials. Accelerated curing provides a better quality product[8].

Aim of the Research:

The main purpose of this research included experimental and analytical works in order to define the <u>*best curing method ,*</u> which characterize the mechanical properties (compressive strength) of a Reactive Powder Concrete (RPC), that will meet the performance and durability requirements of concrete pavements in Iraq.

Experimental Program:

Technical and statistical applicability of designed the RPC mix was verified by manufacturing and destructive loading tests (compressive strength tests) of concrete specimens prepared from this type of concrete.

1. Constituent Materials:

The major properties of the constituent materials used in this investigation were given in Table (1).

Table (1): Properties of the constituent materials of RPC

Material	Properties
Portland cement	Turkish, Elazig, CEM I 42.5 N, physical tests were done according to ASTM Specifications[9,10,11,12], and chemical tests were done according to Iraqi Specifications[13], results were tabulated in Tables (2 and 3).
Silica fume-HR	(grey color), it contains extremely fine (0.1 μm) latently reactive silicon dioxide, its dry bulk density is 0.65 ± 0.1 kg.
Polymers*	(Sika® Mono Top-110 SL), a self-leveling cementitious polymer modified one-compound ready-mix mortar screed. It is used as a substrate for carpet, ceramic marble, PVC coats, etc.
Fine sand	Two types of natural fine sand were used: <u>*Danadan fine sand*</u>, is a river sand, has a black color and it is taken from Tigris River in the south of Mosul city; and <u>*Kanhash fine sand*</u>, is widely obtained from Kanhash village near Mosul city with yellow-brown color. The two types of fine sand were prepared in accordance with BS : 882 : 1992[14]. Their fractions of different sizes were shown in Table (4).
Quartz flour**	(Sikadur 504 C), a powdered quartz flour with a mean particle size (10-15 μm.) was used as micro filler, its bulk density is between (1.5-1.7) kg/l.
Superplasticizers (Accelerator)	Two types of HRWA agents were used: (a) <u>*Sikament-163*</u> is used as a highly effective water-reducing agent and superplasticizer, it complies to ASTM C494 – type F and BS : 5075 : Part 3 for superplasticizers, it has a brown color, its density is 1.2 kg/l, and pH is (10 ± 1.0); and (b) <u>*ViscoCrete-5W*</u> is a 3rd generation superplasticizer for concrete and mortar.

*** Polymer's technical data are:**
(a) It it is a grey cement;
(b) It it is easy to apply with good flowability;
(c) It gives a high early and final mechanical strengths;
(d) It is a non-toxic substance, and economical in use; and
(e) Its density is approximately 2.025 ± 0.125 kg/lt.
**** Sikadur 504 C contains a medium degree of aggregates filling, therefore, it can be used in a number of varying applications:**
(a) As bonding mortar on stone, concrete, etc.;
(b) For vertical and overhead filling of cavities;
(c) As mortar for damaged concrete joint edges and concrete roads.
(d) As abrasion resistant and impact resistant wearing courses;
(e) For structural bonding of wide joints; and
(f) For high mechanical strengths.

Table (2): Physical properties of the used cement[9,10,11,12]

Properties	Used Cement	Typical values

Normal consistency (%)	31	25 – 35
Blain fineness (cm^2/gm)	3000	2300, min.
Initial setting time (minutes)	165	45 min., min.
Final setting time (minutes)	275	600 min., max.
3-day comp. strength (MPa)	20.20	15.0, min.
7-day comp. strength (MPa)	30.60	23.0, min.
Soundness, Autoclave test, (%).	0.60	0.8, max.
Loss on ignition (%)	1.87	4.0, max.

Table (3): Chemical properties of the used cement[13]

Oxides content (%)	Used Cement	Typical values
CaO	62.35	60-67
SiO_2	21.15	17-25
Al_2O_3	7.00	3.0-8.0
Fe_2O_3	5.09	0.5-6.0
MgO	2.86	0.1-4.0
SO_3	2.33	1.0-3.0
C3S	34.013	--
C2S	35.02	--
C3A	2.60	--
C4AF	24.32	--
Insoluble residue	0.64	1.5, max

Table (4): Gradation of fine sand

Sieve size		Percentage retained on each sieve (%)	Cumulative percentage retained on each sieve (%)	Percentage passing of each sieve (%)	FINE SAND (BS:882:1992)
BS (mm.)	ASTM				
4.75	No.4	0	0	100	100
2.36	No.8	0	0	100	80 – 100
1.18	No.16	0	0	100	70 – 100
0.600	No.30	10	10	90	55 – 100
0.300	No.50	80	90	10	5 – 70
0.150 (Pan)	No.100 (Pan)	10	100	--	--
Fineness Modulus		1.00			

Note: Both types of sand were prepared by washing them on sieve No. 200 to remove particles finer than sieve No.200[15], drying them in ovens for (24) hours at (100-110)^{o}C, separating each type of sand in many sizes using the standard sieves used in sieve analysis of fine aggregates, then mix these individual sizes using the calculated satisfying percentages retained on each sieve to prepare the tested samples used in cast concrete specimens.

2. Mixture Proportions:

Two basic varieties of RPCs were produced : one group with polymers and the second group without polymers. Sixteen trial mixes were prepared and cast in this investigation, in order to obtain the *Best Curing Method* out of *five* curing regimes, in relation with compressive strength. Triplicate cube specimens were used in testing the compressive strength for each age of test. The details of mixture proportions were tabulated in Tables (5 and 6).

No. of Specimens = No. of batches x No. of curing regimes x No. of specimens/ batch, therefore,
No. of specimens = 16 x 5 x 9 = 720.

Table (5): Mixture proportions for mixes without polymers

Mixture No.	1	2	3	4	5	6	7	8
Materials	Amounts (kg/m^3)							
Turkish cement (OPC)	800	800	800	800	800	800	800	800
Silica fume-HR	200	200	200	200	200	200	200	200
Polymers (Sika MonoTop-110 SL)	--	--	--	--	--	--	--	--
Cementitious Materials	1000	1000	1000	1000	1000	1000	1000	1000
Danadan fine sand	760	--	760	--	960		960	--
Kanhash fine sand	--	760	--	760	--	960	--	960
Quartz flour (Sikadur 504 C)	240	240	240	240	240	240	240	240
Superplasticizers (Sikament-163) *	60	60	--	--	65	65	--	--
Superplasticizers (ViscoCrete-5W) *	--	--	30	30	--	--	31	31
Water for hydration	224	224	224	224	224	224	224	224
Total weights	2284	2284	2254	2254	2489	2489	2455	2455
Water/cement ratio **	0.280	0.280	0.280	0.280	0.280	0.280	0.280	0.280
Water/cementing materials ratio	0.224	0.224	0.224	0.224	0.224	0.224	0.224	0.224

Table (6): Mixture proportions for mixes with polymers

Mixture No.	9	10	11	12	13	14	15	16
Materials	Amounts (kg/m^3)							
Turkish cement (OPC)	800	800	800	800	800	800	800	800
Silica fume-HR	100	100	100	100	100	100	100	100
Polymers (Sika MonoTop-110 SL)	100	100	100	100	100	100	100	100
Cementitious Materials	1000	1000	1000	1000	1000	1000	1000	1000
Danadan fine sand	760	--	760	--	960	--	960	--
Kanhash fine sand	--	760	--	760	--	960	--	960
Quartz flour (Sikadur 504 C)	240	240	240	240	240	240	240	240
Superplasticizers (Sikament-163) *	60	60	--	--	66	66	--	--
Superplasticizers (ViscoCrete-5W) *	--	--	30	30	--	--	31	31
Water for hydration	224	224	224	224	224	224	224	224
Total weights	2284	2284	2254	2254	2490	2490	2455	2455
Water/cement ratio **	0.280	0.280	0.280	0.280	0.280	0.280	0.280	0.280
Water/cementing materials ratio	0.224	0.224	0.224	0.224	0.224	0.224	0.224	0.224

*** Several trial mixtures were prepared to define the required dosages of the superplasticizers.**
**** Water/cement ratios were adjusted for S.S.D. condition.**

3. Testing of fresh and hardened concrete:

Dry ingredients were mixed first using a mechanical rotary pan type mixer until a homogeneous mixture was reached (based on color and visual appearance). (87)% of the mixing water and (50)% of HRWA admixture were added and mixed for two minutes, the remaining mixing water and HRWA admixture were added, and the mixing was continued until the RPC mixture changes from a dry powder to a thick paste, then stop mixing. At this moment, the measurement of the workability was done (fluid consistency, i.e., flow was 130 to 180%) applying the flow test, which done according to ASTM C1437[16]. The steel molds were placed on a vibrating table, and the concrete was added in portions while the mold was being vibrated. The vibrating or consolidating time was between (5 and 10) minutes. After filling, specimens were removed from the vibrating table and were screeded, each specimen surface was covered with plastic sheet to prevent moisture loss. The specimens were removed from the molds at the age of (24 ± 2) hours then subjected to the different curing regimes (five types) specified in the research. For each type of curing and at the different test ages, the compressive strength of the RPCs was determined, using the standard cubes of 100x100x100 mm. size. The actual length of cube specimens was measured by a digital vernier, then cubes were tested at ages 3, 7, and 28 days, using an (2000 Kn) capacity testing machine in accordance with the ASTM C192/192 M-02[17].

4. Curing Methods:

The test specimens were cured under five types of curing until the day of testing. These treatments were explained in Table (7).

Table (7): Curing methods applied in the research

Curing Methods				
C1	C2	C3	C4	C5
Modified Curing Specimens are immersed in hot water at 60°C for 7 days starting at one day after cast, specimens are then stored at 23°C & 100% RH until tested at 3, 7, and 28 days.	*Normal Treatment* Specimens are allowed to remain in a standard environment conditions (23°C & 95% RH) starting at one day after cast until tested at 3, 7, and 28 days.	*Delayed Curing* Specimens are subjected to Normal Curing (C2) for 10 days after casting then specimens are subjected to Steam Curing (C4) for 48 hrs, specimens are then stored at 23°C & 100% RH until tested at 14, and 28 days.	*Steam Curing* Specimens are subjected to thermal steam treatment for 48 hrs at 90°C & 100 % RH starting at one day after cast, specimens are then stored at 23°C & 100% RH until tested at 3, 7, and 28 days.	*Steam Pressure Curing* Specimens are autoclaved at 120°C & 1.0 MPa for 3 hours starting at one day after cast, specimens are then stored at 23 °C &100% RH until tested at 3, 7, and 28 days.

Results and Discussions:

Compressive strength results have been tabulated in Tables (8 and 9) and diagrammatically illustrated in Figures (1 and 2). These results are examined in details in the following discussion.

Table (8): Compressive strength results for mixes without polymers (MPa)

Mix No.		1	2	3	4	5	6	7	8
C1 Modified Curing	3	41.14	50.07	43.95	59.66	38.09	50.10	68.05	70.00
	7	45.91	52.74	52.21	64.10	38.21	53.89	73.61	78.30
	28	54.40	63.56	59.20	69.08	46.31	61.67	84.89	89.77
C2 Normal Curing	3	39.21	43.44	41.09	52.21	25.44	41.98	61.03	63.20
	7	39.45	57.04	55.03	58.82	26.98	52.80	67.19	71.65
	28	51.29	60.37	66.24	63.68	29.12	57.37	70.19	76.49
C3 Delayed Curing	14	40.76	54.00	53.26	65.80	36.18	53.53	78.85	81.14
	28	51.48	68.39	61.37	70.06	40.60	53.77	84.56	87.73
C4 Steam Curing	3	36.58	48.24	53.39	43.08	28.96	47.77	54.08	63.14
	7	40.44	54.34	61.46	59.72	32.65	50.21	63.39	73.85
	28	44.94	56.66	64.36	65.04	35.04	54.00	75.36	79.04
C5 Steam Pressure Curing	3	40.83	48.26	56.95	56.33	34.75	48.38	54.92	64.83
	7	42.56	54.59	62.65	61.28	40.75	51.06	63.86	75.03
	28	49.78	55.43	65.27	66.74	41.30	55.49	77.93	82.86

Table (9): Compressive strength results for mixes with polymers* (MPa)

Mix No.		9	10	11	12	13	14	15	16
C1 Modified Curing	3	57.72	44.73	46.79	56.72	58.15	51.12	44.03	52.19
	7	63.86	47.61	53.84	60.34	59.56	55.80	52.86	56.25
	28	67.52	58.79	59.72	68.38	62.08	61.94	60.56	62.09
C2 Normal Curing	3	45.48	33.28	39.69	51.97	41.36	43.47	41.04	38.62
	7	48.66	45.84	44.86	57.52	47.76	44.45	45.40	55.58
	28	56.04	48.59	51.33	66.08	58.39	69.03	66.62	70.12
C3 Delayed Curing	14	60.72	53.83	54.62	64.29	70.69	51.29	58.08	54.93
	28	64.58	62.48	58.38	68.76	73.82	58.53	69.89	60.36
C4 Steam Curing	3	47.63	36.73	44.47	52.54	56.22	41.63	43.21	50.00
	7	52.83	41.93	49.08	56.66	58.95	49.62	52.62	53.80
	28	55.79	45.02	51.53	63.41	61.91	52.84	56.98	61.24
C5 Steam Pressure Curing	3	50.04	39.71	42.27	52.69	57.67	47.81	47.62	52.02
	7	53.51	46.40	45.95	57.84	61.69	53.82	54.36	58.79
	28	57.83	51.25	47.37	61.75	64.45	54.42	62.32	59.58

*** Some mixes with polymers have a higher compressive strength than similar mixes prepared without polymers. This is because of the *coupling process*, which is a chemical bond at the interface between the organic polymer and the inorganic substrate[18], as well as, the polymer's technical data used in this research indicated that it is a grey cement, and it gives a high early and final mechanical strengths.**

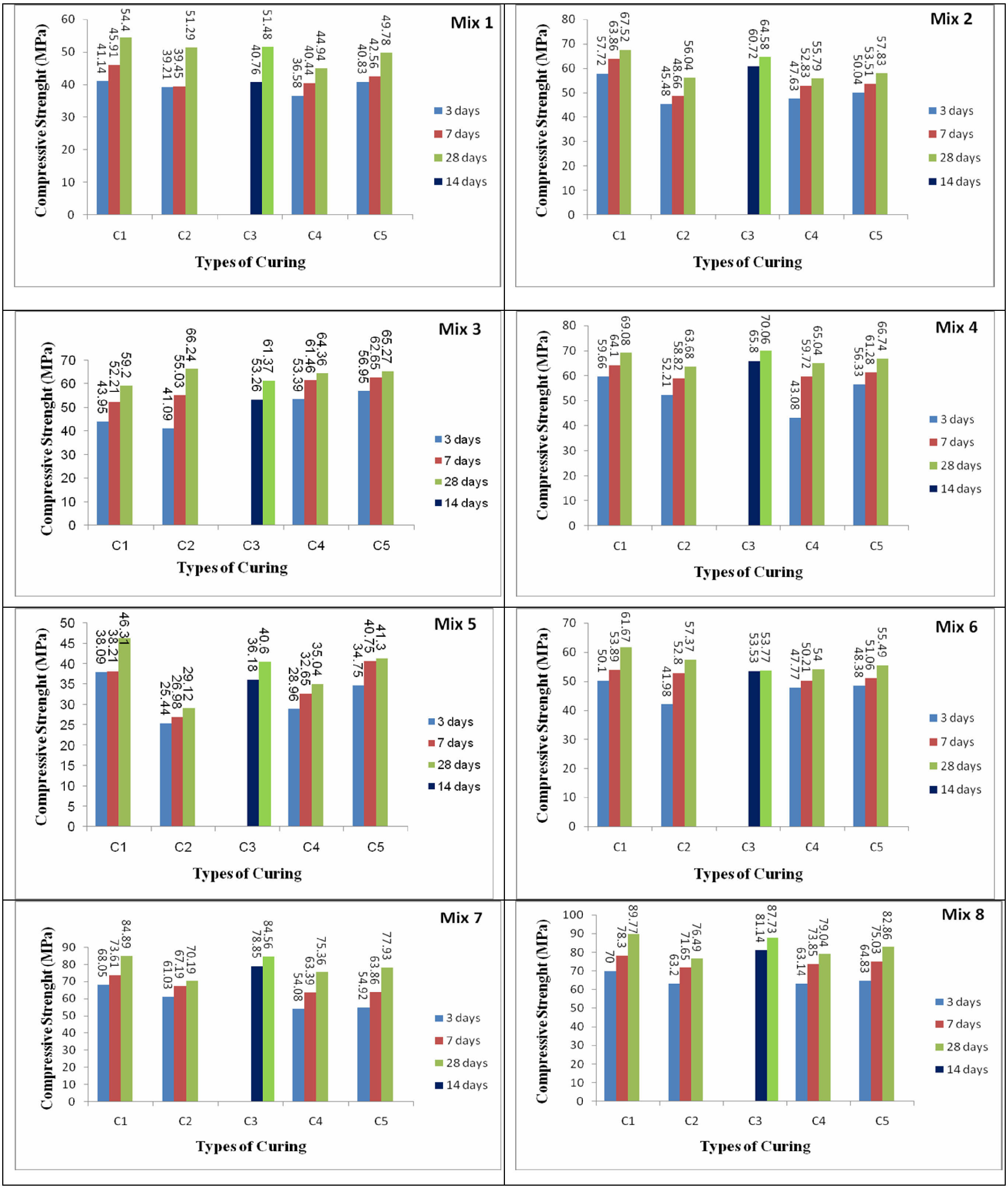

Fig.(1): Effect of Curing Types on the compressive strength of Reactive Powder Concrete (without Polymers)

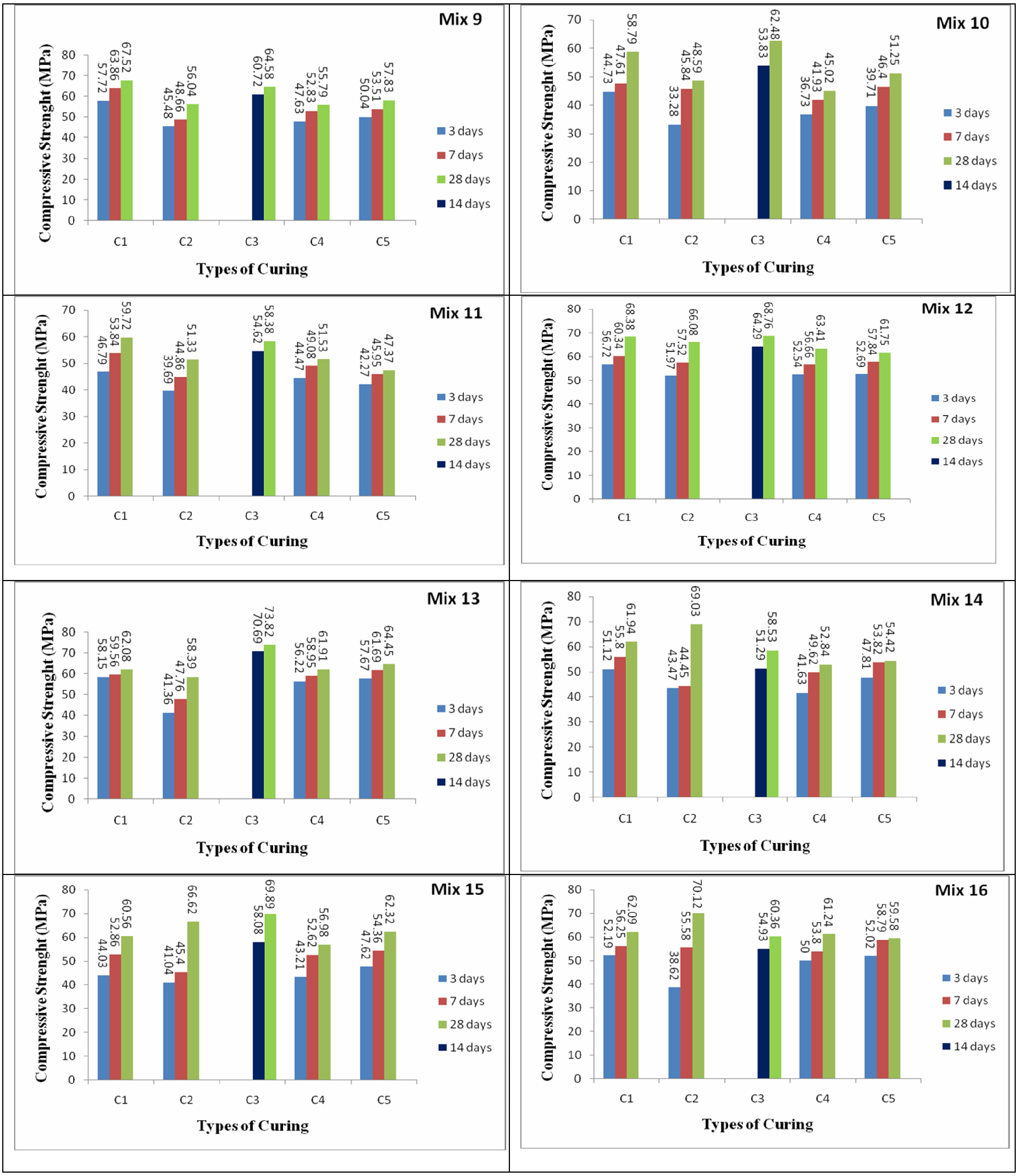

Fig.(2): Effect of Curing Types on the compressive strength of Reactive Powder Concrete (with Polymers)

Compressive strength results, at all ages, indicated that the highest values were produced by both the Modified Curing (C1) and the Delayed Curing (C3). Depending on mix proportions, percentages of increasing in the 28-day compressive strength of concrete with respect to curing types were shown in Tables (10 and 11).

Table (10): Percentages of increasing in the 28-day compressive strength (mixes without polymers)

Mix No.		1	2	3	4	5	6	7	8
Curing Types	Age	Percentage of increasing in the compressive strength (%)							
C1 > C2	28	6.06	5.28	--	8.48	59.03	7.50	20.94	17.36
C1 > C3	28	5.67	--	--	--	14.06	14.69	0.39	2.33
C1 > C4	28	21.05	12.18	--	6.21	32.16	14.20	12.65	13.58
C1 > C5	28	9.28	14.67	--	3.51	12.13	11.14	8.93	8.34
C3 > C2	28	0.37	13.28	--	10.02	39.42	--	20.47	14.69
C3 > C4	28	14.55	20.70	--	7.72	15.87	--	12.21	10.99
C3 > C5	28	3.42	23.38	--	4.97	--	--	8.51	5.88

Table (11): Percentages of increasing in the 28-day compressive strength (mixes with polymers)

Mix No.		9	10	11	12	13	14	15	16
Curing Types	Age	Percentage of increasing in the compressive strength (%)							
C1 > C2	28	20.49	20.99	16.35	3.48	6.32	--	--	--
C1 > C3	28	4.57	--	2.30	--	--	5.83	--	2.87
C1 > C4	28	21.03	30.59	15.89	7.84	0.27	17.22	6.28	1.39
C1 > C5	28	16.76	14.71	26.07	10.75	--	13.82	--	4.21
C3 > C2	28	15.24	28.59	13.73	4.06	26.43	--	4.91	--
C3 > C4	28	15.76	38.78	13.29	8.44	19.24	10.77	22.66	--
C3 > C5	28	11.67	57.34	23.24	11.35	14.54	7.55	12.15	1.31

Where:
C1 = Modified curing;
C2 = Normal curing;
C3 = Delayed curing;
C4 = Steam curing; and
C5 = Steam Pressure curing.

It is clear from Tables (10 and 11), that the percentages of increasing in the 28-day compressive strength of concrete with respect to curing types are as follows:

(a) *For mixes without polymers*:
– C1 recorded (59.03, 14.69, 32.16, and 14.67)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively; and
– C3 recorded (39.42, 20.70, and 23.38)% higher 28-day compressive strength than (C2, C4, and C5) respectively.

(b) *For mixes with polymers*:
– C1 recorded (20.99, 5.83, 30.59, and 26.07)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively.
– C3 recorded (28.59, 38.78, and 57.34)% higher 28-day compressive strength than (C2, C4, and C5) respectively.

The development of good strength is credited to sufficient moisture and suitable vapor pressure, which were maintained to continue the hydration of cement. Furthermore, the pozzolanic reaction between silicon dioxide of silica fume and calcium hydroxide (portlandite) librated from cement hydration occurred due to sufficient moisture available in water.

In order to explain this effect the following principles are discussed[2,6]:

* Pozzolanic silica is added in the stoichiometric quantity necessary to react with all the calcium hydroxide that would be produced assuming complete cement hydration. Using cement chemists' notation, the simplified hydration reaction is :

$$2C_3S + 6H \longrightarrow C_3S_2H_3 + 3CH$$

$$2C_2S + 4H \longrightarrow C_3S_2H_3 + CH$$

[Where : $C = CaO$, $S = SiO_2$, $H = H_2O$]

The $C_3S_2H_3$ is poorly crystalline, and essentially non-stoichiometric; accordingly it is more commonly referred to as (C – S – H) or calcium silicate hydrate. The calcium hydroxide

[CH] produced by hydration occupies (20 – 25)% of the cement paste by volume and makes no contribution to strength and durability. Addition of amorphous silica forms further desirable (C – S – H) at the expense of calcium hydroxide, according to the "pozzolanic reaction":

CH + S + H   C – S – H

* For mixes cured at elevated temperatures other than normal curing, the (CaO/SiO_2) ratio in the binder is reduced by the addition of further silica. This modifies the hydration sequence further, as shown below, resulting in a lower-lime (C – S – H) that ultimately converts to crystalline tobermorite [$C_5S_6H_5$], conferring higher strength to the hardened concrete: (C3S + C2S) + S + H $C_3S_2H_3$ + CH + S   C – S – H $C_5S_6H_5$ At these elevated temperatures, finely divided crystalline forms of silica are sufficiently reactive to act pozzolanically, so ground quartz flour is normally employed and highly siliceous aggregate can also contribute this reaction.

On the other hand, some mixes with polymers have a higher compressive strength than similar mixes prepared without polymers. This is because of:

(a) The *coupling process*, which is a chemical bond at the interface between the organic polymer and the inorganic substrate, since polymer concrete (PC) is a composite material formed by combining mineral aggregates such as sand with monomer[18]; and (b) The polymers used in this research indicated that it is a grey cement, and it gives a high early and final mechanical strengths.

Conclusions:

Based on the experimental results and discussion of this research, the following conclusion can be drawn:

Both the *Modified Curing* (C1) and the *Delayed Curing* (C3) were the most effective methods of curing. They produced the highest values of compressive strength at all ages. Depending upon mix proportions and age of test, the percentages of increasing in the 28-day compressive strength of concrete with respect to curing types are as follows:

(a) For mixes without polymers:

– C1 recorded (59.03, 14.69, 32.16, and 14.67)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively; and

– C3 recorded (39.42, 20.70, and 23.38)% higher 28-day compressive strength than (C2, C4, and C5) respectively.

(b) For mixes with polymers:

– C1 recorded (20.99, 5.83, 30.59, and 26.07)% higher 28-day compressive strength than (C2, C3, C4, and C5) respectively. and

– C3 recorded (28.59, 38.78, and 57.34)% higher compressive strength than (C2, C4, and C5) respectively.

Recommendations:

We suggest another research to study the effect of accelerated curing, such as boiling water; high temperature at 150^{o}C/3 days; autoclaved with 217^{o}C/2.0 MPa/2,3 days; 500^{o}C temperature for (2) hours in a muffle furnace; fog room (60% humidity); and burning, on strength of (RPC).

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