

Civil and Architectural Engineering

Effect of Fly Ash on Some Properties of Reactive Powder Concrete

Zahraa Fadhil Muhsin *
Civil Engineering Department
College Of Engineering
University Of Baghdad
Baghdad, Iraq
z.muhsin1901m@coeng.uobaghdad.edu.iq

Prof.Dr. Nada Mahdi Fawzi
Civil Engineering Department
College Of Engineering
University Of Baghdad
Baghdad, Iraq
nada.aljalawi@coeng.uobaghdad.edu.iq

ABSTRACT

To achieve sustainability in the field of civil engineering, there has become a great interest in developing reactive powder concrete RPC through the use of environmentally friendly materials to reduce the release of CO₂ gas produced from cement factories as well as contribute to the recycling of industrial wastes that have a great impact on environmental pollution.

In this study, reactive powder concrete was prepared using total binder content of 800 kg/m³, water to binder ratio (0.275), and micro steel fibers 1% by volume of concrete. The experimental program included replacing fly ash with (8, 12, 16) % by cement weight to find the optimal ratio, which achieved the best mechanical properties of (RPC) at 7, 28, and 90 days with standard curing. Some mechanical properties of reactive powder concrete (flow, compressive strength, tensile strength, and density) were verified. The results at 28 days showed that the compressive strength (96.5) Mpa, tensile strength (9.38) Mpa, and density (2395 kg/m³). The results showed that the percentage of replacement of 8% of fly ash with cement is the optimal percentage, which achieved the highest resistance compared to the others. The results also indicated that it is possible to develop RPC using fly ash with a high withstand stress, tensile strength, and density.

Keywords: sustainability, reactive powder concrete(RPC), Fly ash (FA), cement, tensile strength.

تأثير الرماد المتطاير على بعض خواص خرسانة المساحيق الفعالة

إ.د. ندى مهدي فوزي
قسم الهندسة المدنية

*زهراء فاضل محسن
قسم الهندسة المدنية

الخلاصة

لتحقيق الاستدامة في مجال الهندسة المدنية، أصبح هناك اهتمام كبير بتطوير خرسانة المساحيق الفعالة من خلال استخدام مواد صديقة للبيئة، لتقليل إطلاق غاز ثاني أكسيد الكربون الناتج من مصانع السمنت وكذلك المساهمة في إعادة تدوير

*Corresponding author

Peer review under the responsibility of University of Baghdad.

<https://doi.org/10.31026/j.eng.2021.11.03>

2520-3339 © 2019 University of Baghdad. Production and hosting by Journal of Engineering.

This is an open access article under the CC BY4 license <http://creativecommons.org/licenses/by/4.0/>.

Article received: 27/5/2021

Article accepted: 5/7/2021

Article published:1/11/2021



المخلفات الصناعية التي لها تأثير كبير على تلوث البيئة. تضمن البرنامج التجريبي استبدال الرماد المتطاير بنسب (8 ، 12 ، 16)٪ وزن السممت لإيجاد النسبة المثلى التي تحقق أفضل الخواص الميكانيكية لـ (RPC) ، في 7 و 28 و 90 يوماً بالمعالجة القياسية. في هذه الدراسة خرسانة المساحيق الفعالة تم اعدادها باستخدام سممت 800 كغم / م³ ، ونسبة الماء إلى المادة الرابطة حوالي (0.275) وألياف الصلب الدقيقة 1٪ من حجم الخرسانة. تم التحقق من بعض الخواص الميكانيكية لخرسانة المساحيق الفعالة (التدفق ، مقاومة الانضغاط ، قوة الشد والكثافة). أظهرت النتائج عند 28 يوم أن مقاومة الانضغاط (96.5) ميكا باسكال ومقاومة الشد (9.38) ميكا باسكال والكثافة (2395 كغم / م³). أظهرت النتائج أن النسبة المثوية لاستبدال 8٪ من الرماد المتطاير بالسممت هي النسبة المثلى والتي حققت أعلى مقاومة مقارنة مع النسبة الأخرى. كما أشارت النتائج إلى أنه من الممكن تطوير خرسانة مساحيق فعالة باستخدام الرماد المتطاير بمستوى عالٍ من تحمل الإجهاد و مقاومة الشد و الكثافة .

الكلمات الرئيسية : الاستدامة ، خرسانة المساحيق الفعالة (RPC) ، الرماد المتطاير (FA) ، السممت ، مقاومة الشد .

1. INTRODUCTION

The need for high strength requirements with the high performance of concrete was the main reason for the production of reactive powder concrete (RPC). The first person who began to search for this type of concrete was Richard Cheyrezy from 1990 to 1995. It became possible to produce RPC concrete by establishing and presenting basic structure, preparation, and mixing (**Richard, 1995**). Reactive powder concrete (RPC) is a modern cement composite material with high performance and good durability properties and has been applied in a wide field of protective engineering. The addition of fiber to RPC improved its compressive strength properties compared to conventional concrete. (**Xu, 2016**). Fly ash is one of the wastes generated from electric power plants, which relies on coal as fuel. When coal is burned, it will pass into the furnace through the high-temperature region, in which the volatile material is burned with carbon. fly ash was used to produce a type of cement called blended cement, where it was added to clinker and gypsum and crushed. (**Zongjin Li, 2011**).

The main benefits of using fly ash in concrete are summarized as follows:

- Due to the spherical nature of fly ash particles and the packing effect property, which helps to improve workability and reduce the amount of water required.
- The high surface area increases pozzolanic activity and thus improves the gain strength.
- Improve the consistency of the concrete mixture and reduce its variability through the harmonic distribution of particles within the mixture (**Zongjin Li, 2011; Yu J and Leung CKY, 2017**).

(**Kadhun, 2015**) assessed the mechanical properties of the compressive strength and flexural strength of the RPC by using steel fibers. The results show that the addition of steel fibers led to a significant improvement in compressive strength and bending compared to concrete without steel fibers. (**Algburi et al., 2019**) also recorded the ratio of the compressive strength of RPC reinforced with fiber at the age of seven days to the compressive strength of RPC at the age of 28 days which was higher than that of non-fiber reinforced RPC by 33%, which made it suitable for use in structural elements that need high early compressive strength such as bridges, buildings rising and structural columns. (**Elsayed et al., 2019**) succeeded in obtaining a compressive strength of 121 MPa by producing PRC by using silica and fly ash at a life of 28 days and under normal conditions where the percentage of silica that achieved the highest resistance was 25% replaced by cement weight with a w/c ratio of 0.25 and the proportion of steel fibers is 2%.

It was also noted that the preparation of reactive powder concrete using fine iron fibers at a ratio of (1- 1.5%) and through water treatment, the amount of compressive strength achieved at the age of 28 days was 70 MPa, where the results showed that the sample containing (1.5%) of fibers is the best for protection because it is very dense (**Fawzi et al., 2020**). In another study (**Yu et al.,**



2018) concluded that a new type of environmentally friendly green concrete could be developed by including a percentage of no less than 80% of fly ash in concrete production. Also, he proved that the use of fly ash in the production of concrete will lead to obtaining suitable workability and good strength in structural construction. (Hüseyin et al., 2012) concluded that it is possible to produce RPC by replacing 60% of the cement weight with fly ash. After conducting the tests to verify the mechanical properties, the results indicated a significant improvement in compressive strength, tensile and flexural strength, as the compressive strength under standard water treatment was 200MPa. (Sarika and John, 2015) checked the mechanical and fresh concrete properties of reactive powder concrete. They show the ability to produce RPC at a compressive strength of 130 MPa under standard processing conditions at 28 days of life. The strength obtained at 28 days of curing is equivalent to approximately 70% of the strength achieved at 7 days.

This research aims to use sustainable fly ash as a partial substitute for cement weight and to ascertain its effect in improving the mechanical properties of reactive powder concrete. Thus, reducing the amount of cement that makes up the bulk of the components of reactive powder concrete, as the cement manufacturing process is one of the main sources responsible for the release of carbon dioxide and the cause of global warming, in addition to contributing to the protection of the environment from pollution through the recycling of fly ash waste.

2. EXPERIMENTAL WORK

2.1 Materials

2.1.1 Cement

The Ordinary Portland cement (OPC) used in this study is within the Iraqi Specification **IQS No. 5/2019 type / (42.5 N)**. **Table.1** shows the chemical and physical analysis of the cement used in this work. **Table.2** shows physical analysis of cement.

Table 1. The chemical analysis of the cement.

compound composition	Test Result		limit of Iraq specification No5-2019
Lime(CaO)	62		--
Silica (SiO ₂)	22		--
Alumina (AL ₂ O ₃)	5.3		--
Iron oxide (Fe ₂ O ₃)	3.4		--
Sulfate(SO ₃)	2.2	C3A<5	Max 2.5
		C3A>5	Max 2.8
Magnesia (MgO)	2.1		Max 5



Insoluble Residue) (I.R)	0.9	Max 1.5
Loss On Ignition (L.O.I)	2.5	Max 4

Table 2. Physical analysis of cement.

Propriety	Test Result	limit of Iraq specification No5-2019
Fineness Blaine cm ² /gm.	3400	Min 2500
Initial setting time	140min	Min 45 min
Final setting time	368 min	Max 10 hr.
Specific gravity	3.14	
Compressive Strength (Mpa)		
2 day	15.22	10Min
28 day	54.5	Min 42.2

2.1.2 Fine Aggregate

AL-Ukhaider Natural sand as a fine aggregate was used in concrete mixes of this work. The chemical and physical properties of the sand are within the limit specified by Iraqi standard, **zone /4. IQS No.45/1984**. As shown in **Table 3**.

Table 3. Aggregate gradation, chemical and Physical Properties of Fine aggregate.

Sieve size (mm)	Cumulative Passing %	Limits of Iraqi spec.No.45/1984/Zone 4
10	100	100
4.75	100	95-100
2.36	100	95-100



1.18	100	90-100
0.6	82.3	80-100
0.3	16	15-50
0.15	6	0-15
Physical and Chemical properties		Test
		Limits of Iraqi spec. No.45/1984
fineness modulus:	2.6	-
% SO ₃	0.32	Max 0.5%
Specific gravity	2.5	-
Absorption%	1.18	-
dry rodded density Kg/m ₃	1680	-

2.1.3 Mixing water

The water used in this research within Iraqi to specification **No.1703/1992** .

2.1.4 Silica fume (SF)

Micro silica from Company (CONMIX) was used in this work. The percentages used were 10%, replacement with cement weight, and it is within the requirements of **ASTM C1240-15**. Chemical and physical analysis of silica as shown in **Table 4**.

Table 4. Chemical and physical properties of silica fume.*

Oxide composition	Oxide content	ASTM C1240-2015
SiO ₂	89.2	min 85%
Al ₂ O ₃	1.3	-
F ₂ O ₃	1.8	-
MgO	2.3	-
L.O.I	2.5	6%



CaO	2.5	-
<i>Physical properties</i>		
Specific gravity	2.16	
fineness	1600g/m ³	
Physical form	powder	

manufacture properties. *

2.1.5 Fly ash (FA)

Fly ash was used in this research according to the standard to American Standard **ASTM C 618-15**. In this research Fly ash Class (F) with (8) % proportion was used as replacements of cement weight. Chemical and physical analysis of Fly ash is given in **Tables 5** and **6**.

Table 5. Chemical analysis of fly ash.

compounds	content%		Specification 618-C ASTM Class F
SiO ₂	61.95	93.44	Minimum 70%
Fe ₂ O ₃	2.67		
Al ₂ O ₃	28.82		
CaO	0.88		-
MgO	0.34		-
SO ₃	4.3		Maximum 5%
Na ₂ O	0.26		-
L.O.I.	5.6		Maximum 6%



Table 6. Physical analysis of fly ash.

Physical appearance	Powder's
The color	Gray
Specific weight	2
Surface area (Blaine method) cm ² / gm	6200

2.1.6 Micro steel fibers (Msf)

The (Msf) used in this test program was straight steel fibers manufactured in China. The diameter of fiber used 0.2 mm and the length 13mm so ($L/d = 65$). Fibers were added at 1% of the concrete volume.

2.1.7 Superplasticizer (SP)

Master Glenium 51(SP), according to **ASTM C494 - 17** was used in this research. The manufacturer's recommended dosage was in the range (0.5-1.6) liters /100kg of the cement. The cement dosage used in this study was 1 liter /100 kg.

2.2. Concrete Mixes

The mixtures were prepared in this work by experimental mixtures based on specifications and guidelines presented in the previous research (Osama, 2018) (**El-Louh,2014**). The batches were prepared as a trial to obtain a compressive design strength of 90 MPa, as the reference mixture for comparison with other mixtures. A total number of four Reactive powder concrete (RPC) mixtures were prepared by using a water to binder ratio of about (0.275). The content of the binder used in this research is 800 kg/m³, HRWR (Glenium 51) used 8 liters by weight of cement. The experiment program included made the control mix with only Portland cement in addition to silica fume (PC+SF) as the binder, while other mixtures included replacing the cement with Fly ash (FA) (PC+ +SF+FA) in which a percentage of PC was replaced with Fly ash (FA) at 8%, 12%, and 16 %. Mix proportions details for RPC are shown in **Table 7**.



Table 7. Details of mix proportion of RPC.

Mix	OPC (Kg/m ³)	Details	SF (Kg/m ³)	Fa (Kg/m ³)	Fine Agg (Kg/m ³)	Weight Water (Kg/m ³)	Msf 1% By vol of concrete
Mr	800	-	80	-	880	220	1
M1	800	8%FA	80	64	880	220	1
M2	800	12%FA	80	96	880	220	1
M3	800	16%FAC	80	128	880	220	1

2.3 Testing

2.3.1 Pozzolanic Activity Index

Pozzolanic Activity Index found in this study for both fly ash with silica and according to (ASTM C311- 16) [96] and (ASTM1240-15) [92] respectively.

2.3.2 Flow test

The RPC flow was calculated in this study according to the **ASTM C-1437-15** specification requirements. Flow is an increase in the original diameter of the concrete source as a percentage to Flow Table Cone (100 mm). Equation 1. Illustrate the flow of PRC.

$$D \text{ Flow} = [(D-100)/100] \times 100 \tag{1}$$

D: The spread rate in the base diameter for concrete from four directions measured, (mm).

2.3.3 Compressive strength test

Compressive strength test was done according to **ASTM C109** by using standard cube specimens of 50x50x50mm. The Compressive strength (*fm*) is calculated with the following equation.

$$fm = P/A \tag{2}$$

fm = compressive strength in mpa



P= total maximum load in N
 A=area of loaded surface in mm²

2.3.4 Splitting tensile strength test.

The tensile strength was determined in this study according to **ASTM C 496**. This test was performed using a standard cylinder model of 100 ×200 mm. (T) calculated according to the following equation:

$$T = 2P / \pi ld \tag{3}$$

Where:

- T: Splitting tensile strength (MPa)
- P: Max. Applied load (N)
- l: is the length of specimen (mm)
- d: Diameter (mm)

2.3.5 Density Test

The density test in this paper was performed according to the American standard **ASTM C642-13**. The density was calculated by dividing the weight of a cube by its volume. Samples were tested at 7, 28, and 90 days old.

3. RESULTS AND DISCUSSION

3.1 Strength Activity Index

The results of the pozzolanic activity test at the age of 7 days of the materials that were used in this research were illustrated as shown in **Table 8**.

Table 8. Strength activity index (S.A.I) of materiel at 7 days.

The mixture symbol	S.A. I%	Limitations of the specification ASTM -C311
Ref	100	-
FA	96.89	≥ 75
SF	110.7	≥ 105



3.2 Workability

The results of the flow test in **Table 9** and **Fig. 1** show that the flow increased with increasing the replacement rates of fly ash by about 35% and that the water demand has decreased compared to the reference mixture while maintaining stable workability. This is due to the small size of the fly ash particles in addition to the glassy texture and the spherical shape that makes it work as spherical bearings lubricate the mix. Thus it acts as a superior plasticizer that increases workability and reduces the amount of water required that increases workability. Also, the spherical shape and smooth surface of the fly ash particles helped reduce the friction that occurs between the particles and make them have greater fluidity. The fly ash particles present on the cement dough surface have an opposite charge, which helps to create a greater dispersion and prevent the Prevent clumps that occur in it (**Mehta, 2006**).

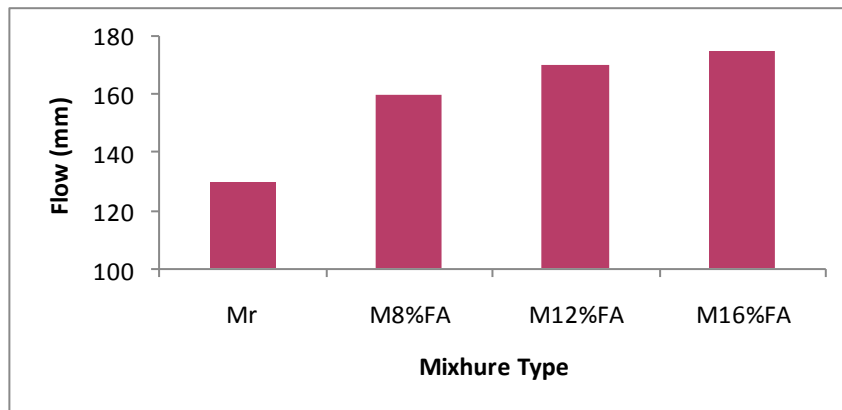


Figure 1. The flow of RPC with changing substitution ratios for fly ash.

Table 9. Effect of FA on workability.

Mix NO.	Fly Ash%	Flow (mm)
Mr	0	130
M1	8%	160
M2	12%	170
M3	16%	175



3.3 Compressive Strength

The results of the average compressive strength of three cubic samples that were prepared in this study are summarized as shown in **Fig. 2.** and **Table 10.** The results showed that the increase in the replacement ratios of cement with fly ash led to an improvement in the compressive strength of concrete during different ages. The sample M1 achieved a compressive strength of (75.7, 96.5, 115.5) and the percentage of increase in strength was (2.6, 4.9, 5.5)% compared to the reference mixture during ages 7, 28, and 90 days, respectively. This increase is a result of the pozzolanic activity of fly ash resulting from the interaction of SiO₂ and Al₂O₃ with CH and the formation of C-S-H, and these reactions result in the formation of a matrix with high density and low porosity and thus an improvement in concrete strength (**Tahir, 2005**) and (**Malvar, 2006**), as well as particle capacity. Fly ash to fill the voids in the cement paste through its contribution to filling led to an increase in density and thus increased strength.

Table10. Effect of FA on RPC compressive strength.

Mix NO.	Compressive strength in (MPa)		
	7day	28day	0da 9y
Mr	73.78	91.95	109.5
M1	75.7	96.5	115.5
M2	74.2	94.9	112.5
M3	73.4	94.1	110

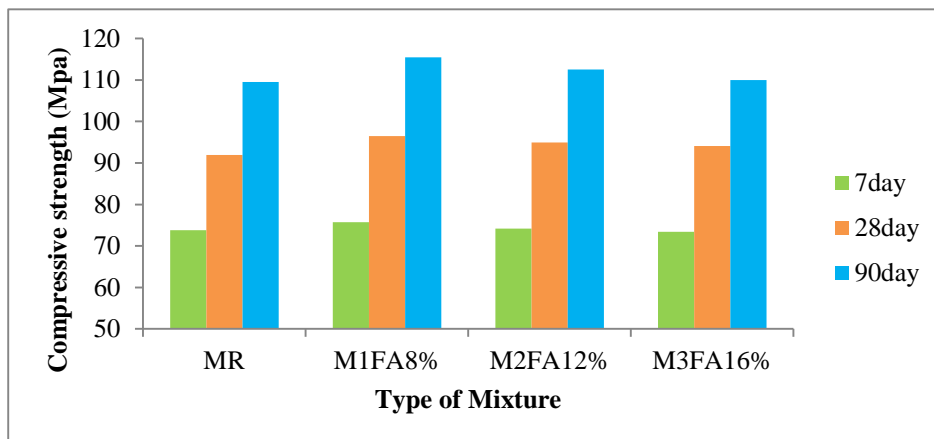


Figure 2. Relationship between Fly ash (FA) percentage and compressive strength of RPC.



3.4 Splitting Tensile Strength Test:

After determining the optimum ratio of fly ash (FA) in the previous stage through the compressive strength test, the tensile strength of the samples that included 8% FA were tested. The results are shown in **Table 11**, and **Fig. 3** summarized the tensile strength of the samples at ages (7, 28, and 90).

Table11. Splitting tensile strength of RPC mixtures.

No/Max	Splitting strength (MPa)		
	7 day	28 day	90 day
M r	4.2	6.3	7.7
M8% FA	6.89	9.38	10.39

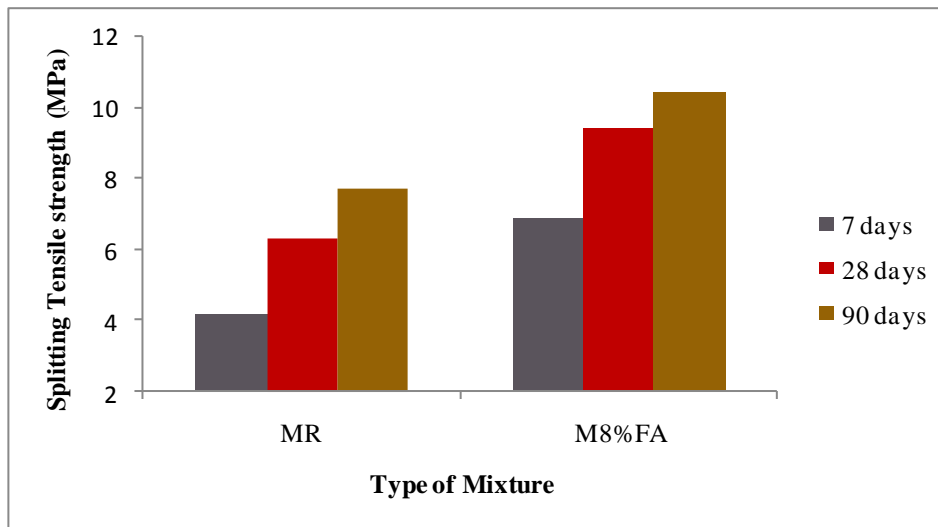


Figure 3. Effect of FA on Tensile strength of RPC.

The apparent improvement in tensile strength is due to the effect of fly ash. The increased hydration leads to the continuation of pozzolanic reactions. This increase may be related to the presence of pozzolanic materials such as fly ash in the composition, whose fineness is less than cement by about five times; this led to improving and strengthening the structure of the concrete material, thus reducing the porosity and increasing the strength of RPC, (Aljalawi, 2009).



3.5 Dry bulk density

Dry density results illustrated in **Table 12** and **Fig. 4** matched what (**Shaheen and Shrive, 2006**) recorded that RPC density ranges from 1760 to 2410 kg / m³. The density of FA samples was higher than the reference samples during ages 7, 28, and 90 days. The reason for this was attributed to the pozzolanic interactions of fly ash with cement and form a dense gel of amorphous C-S-H with the reduction of the porosity and the number and length of the microscopic cracks, thus increasing the bond strength within the concrete network, which results in a high-density matrix compared to the reference samples.

Table 12. Dry bulk density of RPC.

No/Max	bulk density (kg/m ³)		
	7 day	28day	90day
Mr	2373	2385	2393
M8% FA	2383	2395	2402

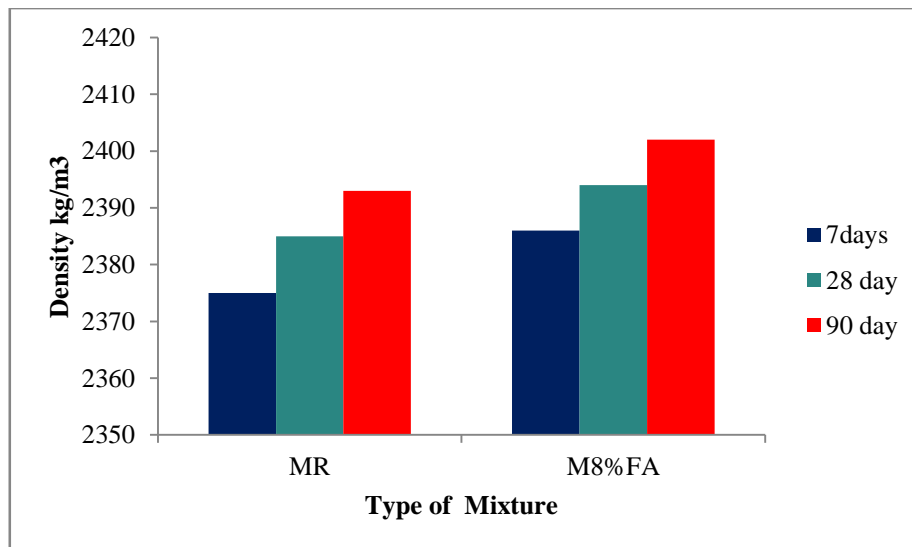


Figure 4 . Effect of FA on the dry density of RPC.



4. CONCLUSIONS

- Increasing the substitution ratios of fly ash with cement from (8-16) % improved the flowability of RPC.
- The compressive strength of RPC increases when (8-12-16)% of fly ash is replaced with cement, and the optimum percentage of FA that achieved the highest resistance compared to reference samples at ages 7, 28, and 90 days is 8%, where it achieved (75.7, 96.5, 115). MPa at 7, 28, and 90 days, respectively.
- When we replace 8% FA, the tensile strength of RPC increases at all ages, and the percentage of increase in tensile strength at the age of 28 days is 48.8% compared to the reference sample.
- The dry density of RPC increases when replacing 8% FA at all ages, compared to the reference samples, and that the RPC density achieved by this replacement ratio is (2383, 2395, 2402) kg/m³ at 7, 28, 90 days.

5. ACKNOWLEDGMENTS

I would like to thank the staff of the Civil Engineering Department, especially all the employees of the Construction Materials Laboratory at the College of Engineering, University of Baghdad, for their continuous support to complete this work.

REFERENCES

- AL Jalawi, N.M.F., 2009. Pozzolanic Activity Index of domestic feldspar, Journal of Engineering, University of Baghdad, College of Engineering, vol .15 - No.2- June.
- AL Jalawi, N.M.F, 2009. Production of high-performance concrete using different types of local pozzolana, Journal of Engineering, University of Baghdad, College of Engineering, vol .15 - No.1-March.
- Al-Jubory, N. H., 2013. Mechanical Properties of Reactive Powder Concrete (RPC) with Mineral Admixture. AL-Rafdain Engineering Vol.28, No. 5.
- ASTM C 109/C109M, 2016. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars Using 2-in. or 50-mm Cube Specimens.
- ASTM C 1240., 2015. Standard Specification for Silica Fume Used in Cementitious, MixturAnnual Book of ASTM Standards.
- ASTM C 496/C496M, 2011. Standard Test Method for Splitting Tensile Strength of cylindrical Concrete Specimens.
- ASTM C 618, 2015. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete.
- ASTM C1437-15, 2015. Standard Test Method for Flow of Hydraulic cement Mortar.
- ASTM C494-/C494M, 2017. Standard Specification for Chemical Admixtures for Concrete1.
- ASTM C642, 2013. Standard Test Method for density, absorption, and voids hardened concrete.
- El-Louh, O.M., 2014. Fresh and Hardened Properties of Locally Produced Reactive Powder, M Sc Thesis, Islamic University –Gaza.
- Gamal I. K, K. M. Elsayed, M. H. Makhlof, and M. A., 2019. Properties of Reactive Powder Concrete Using Local Materials and Various Curing Conditions. EJERS, European Journal of Engineering Research and Science Vol. 4, No. 6.



- Hüseyin Yiğitler, Serdar Aydın, Halit Yazıcı, Mert Yücel Yardımcı, 2012. Mechanical performance of low cement reactive powder concrete (LCRPC), Journal homepage: www.elsevier.com/locate/compositesb
- Iraqi Specification, No.45/1984. Aggregate from Natural Sources for Concrete and Construction.
- Iraqi Standard Specification No.5, 2019, Portland cement.
- Iraqi Standard Specification, No. 1703, 1992, Water used in concrete.
- M. Osama, R., Amr G., Mona, S., and Amr, M., 2018. Optimizing the Performance of Reactive Powder Concrete, engineering research journal (ERJ), Vol. 2, No. 37, pp. 51-57.
- Malvar, L. J., and Lenke, L. R., 2006. Efficiency of Fly Ash in Mitigating Alkali-Silica Reaction Based on Chemical Composition, Mater. J., Vol. [105] Smith.
- K. A., 2015. Advanced sustainable concrete materials for infrastructure applications. Ph.D. Thesis, Missouri University of science and technology. 103, No. 5, 2006, pp. 319–32
- Mehta, P. Kumar, and Paulo J. M. Monteiro, 2006. Concrete: Microstructure, Properties, and Materials. New York: McGraw-Hill.
- Nada Mahdi Fawzi, Nesreen B. Najib, Shatha D. Mohammed, B. and Wasan Z. Majeed, 2020. "Irradiation Duration Effect of Gamma Ray on the Compressive Strength of Reactive Powder Concrete, Key Engineering Materials, Vol. 857.
- P.K. Mehta., 2004. High-performance, high-volume fly ash concrete for sustainable development. Materials Science.
- Richard, P., and Cheyrezy. M., 1995. Composition of reactive powder concretes. J. Cem. Concr. Res. 25, 1501–1511
- Sarika .S, and Dr. Elson John, 2015. A Study on Properties of Reactive Powder Concrete. International Journal of Engineering Research And, V4(11), 110–114.
- Shaheen, E. and Shrive, N. G., 2006. Optimization of Mechanical Properties and Durability of Reactive Powder Concrete, ACI Materials Journal, Vol. 103, No. 6, pp. 444-451.
- Tahir, M. A., and Sabir, M., 2005. A Study on Durability of Fly Ash-Cement Mortars, presented at the 30th Conference on Our World in Concrete and Structures, Singapore, Aug. 23–24, Singapore Concrete Institute, Singapore, 7p.
- Xu. J, Wu, C., Xiang, H., 2016. The behavior of ultra-high performance fiber reinforced concrete columns subjected to blast loading. Eng Struct 118:97–107.
- Yu, J., and Leung, CKY., 2017, Strength improvement of strain-hardening cementitious composites with ultrahigh-volume fly ash. Journal of Materials in Civil Engineering 29: 05017003
- Yu, Jing, Dhanada K. Mishra, Chang Wu, and Christopher K.Y. Leung, 2018. Very High Volume Fly Ash Green Concrete for Applications in India, Waste Management and Research, 36.6, 520–26.
- Zongjin, L., 2011. Advanced Concrete Technology.