Effects of plastic fiber straw and metakaolin on the mechanical properties and impact behavior of recycled aggregate concrete

Mohamed Bachar [a] Rebih Zaitri [a*]

[a] Civil Engineering Department, University of Djelfa, 17000 Djelfa, Algeria.

[*] zrebih@yahoo.fr

Abstract

This article presents the individual and simultaneous effects of metakaolin reactive silica and plastic fiber straw on the mechanical properties and impact behavior of concrete made from natural aggregates and those of recycled aggregates containing 50% replacement. The addition of metakaolin alone or with the plastic fibers only improved the mechanical performance of all the mixtures at a later age (90 days). However, the addition of plastic fibers slightly increased the compressive and tensile strengths of natural aggregate concretes with a decrease in those of recycled aggregate concretes. This deficiency was compensated for by the reactive effect of the silica provided by metakaolin. An optimum of 1% has been specified in plastic fibers for compressive strength for all composites. Natural concretes and those recycled without metakaolin and plastic fibers present a fragile behavior, the energy absorbed at the first crack is substantially equal to that at failure. When these components are used simultaneously, their behavior becomes ductile and the fracture energy is significantly higher than the control concrete and that of the first crack.

Keywords: recycled aggregates, natural aggregates, metakaolin, plastic fibers, flexural strength,

I. Introduction

Solid waste has become an imposed by-product of industrial societies. The sustainability of the construction industry does not only mean reducing carbon emissions and preserving the environment, but also moving very quickly towards the supply of natural resources which are heading towards gradual depletion (Akhtar and Sarmah, 2018)[1]. The primary consumption of concrete is second only to water (Zheng et al., 2018)[2].. Among the components of concrete, aggregates represent about 80% of the total volume of concrete (Verian et al., 2018) [3]. According to statistics, the global consumption of natural aggregates was $45{,}10^9$ tons in 2017, and this figure will increase to $66{,}10^9$ tons by the end of 2025 (Breto and Agrela, 2019) [4]. Recycled aggregates from construction and demolition waste can be used in many civil engineering works, which can contribute significantly to the economic and environmental sustainability of the country (Tunc et al., 2018) [5]. Greater attention has been paid to recycled concrete, for the management of demolition waste landfills (Jiang et al., 2019) [6].Ductility is a parameter that effectively fits into various regulations of concrete, which is why the excessive consumption of reinforcement concrete lies in its poor definition. The waste of organic and inorganic fibers improves this property and aims to save the used steel concrete materials. Concrete is a brittle building material having excellent compressive properties with very low tensile or shear strength. This weakness is usually due to micro cracks occurring at the aggregate-mortar interface. To overcome this, fibers can be added as reinforcements to concrete. Afroz et al.[7]., confirms that concrete made from plastic fibers (PET) develops a higher tensile strength than concrete without fibers. Oroushian et al. [8]. have experimentally proved that the impact resistance of concrete made of PET fibers uniformly dispersed in the concrete matrix is higher than that of ordinary concrete, on the other hand the compressive and flexural strengths are low. Prabhu et al. [9]. also found that PET fibers increase both absorption energy and ductility. The highest ductility is noted for a fiber percentage of 1.5%.Many studies have been carried out on the effect of static loads on the mechanical properties of recycled aggregate concretes [10-19]., while very few have addressed their behavior under dynamic loads, eg. under impact. Only one reported study was conducted by Rao et al. [20]., where the effect of impact loads on the mechanical performance and absorption energy of concrete at different RCA contents was made. Previous studies targeting recycled aggregate concrete; show that the mechanical performance of the latter is low compared to those made from natural aggregates because of the presence of old mortars adhered to their surface (Kou et al., 2012), (Bravo et al, 2015; Mukharjee and Barai,2014) [21-23]. Metakaolin (MK) is a material of strong pozzolanity obtained after calcination of kaolinite in a temperature range between 500 ° C and 800 ° C. its reaction with calcium hydroxide ($CaOH_2$) produces an additional (C-S-H) gel , thus improving the properties of recycled concrete. Its fines penetrate the voids of the RAC and improve mechanical properties and durability (Siddique and Klaus, 2009) [24]. Some previous studies show that compressive strength and tensile strength were significantly improved using 10% MK in RAC (Radonjanin et al., 2013; Singh and Singh, 2016) [25-26].. Others have found that 15% MK improves the mechanical properties and durability of RAC (Kou et al., 2011) [27]. Other studies have indicated a replacement threshold of 30% in recycled aggregates beyond which the mechanical resistance is affected (Mehfteh et al., 2013) [28].

II. Experimental program

II.1. Materials

The chemical composition of the cement and that of the metakaolin powder and which are used in the composition of the concretes is presented in table.1. A substitution of 50% of natural aggregates in those recycled was carried out in the different granular classes (4/10,10/15,15/25), their physical properties are illustrated in Table 2. All aggregates were in saturated and surface dry condition. the plastic fiber straws used as reinforcements in the different formulations in control concrete and recycled for different volume fractions (0.5%,1%,1.5%) have a length of 3cm and a diameter of 1mm with a density of 1.38. the different formulations are presented in table.3. Regarding the compressive strength, four cures of hardening were taken into account: 7, 14, 28 and 90 days. A hydraulic press with a maximum capacity of 3000 KN was used on cylindrical samples of 150ϕx300 mm to measure the compressive strength, according to the standard ASTM C39/C39. The curing times considered for the flexural strength tests were 7, 14, 28 and 90 days, and following ASTM C78 standards. , it was tested on prism 150x150x530 mm specimens. The impact resistance of the test pieces was determined in accordance with the experimental method proposed by the ACI544 committee [29]. Dimensions 150

× 64 mm cut will be rigidly placed on a base plate and struck with repeated blows until the first crack and ultimate failure. The blows were applied with a 4.45 kg hammer dropped several times from a height of 457 mm on a steel ball 63.5 mm in diameter, placed above the upper surface of the cylindrical sample.

Table 1. Physical and chemical properties of cement and clay ceramic powder (Mec).

Composition	Cement	Mec
SiO_2	39.06%	44.47%
Al_2O_3	9.88%	38.50%
CaO	42.82%	0.43%
Fe_2O_3	2.03%	10.73%
SO_3	2.30%	1.60%
MgO	1.54%	
Na_2O	1.73%	
K_2O	1.62%	1.93%
TiO_2		1.02%
CuO		0.70%
Density	2687 kg/m^3	2658 kg/m^3
Blaine surface	4620 m^2/kg	6478 m^2/kg

Table 2. Physical properties of coarse aggregates.

Aggregates	Size(mm)	Bulk Specific Gravity (Saturate Surface Dry, SSD) (kg/m^3)	Bulk Specific Gravity (kg/m^3)	Apparent Specific Gravity (kg/m^3)	Absorption(%)
NCA	4--10	2677	2631	2770	1,8
	10--15	2688	2644	2774	1.7
	15--25	2701	2664	2773	1.6
RCA	4--10	2510	2377	2721	4.7
	10--15	2528	2398	2720	4.1
	15--25	2534	2430	2722	3.2

Table 3. Concrete mixtures for the different series of specimens

Mix	Cement	Water	Mec	Sand	NCA	RCA	RPFW(%)	SP	Slump(cm)
CNC	400	210		640	1170			2.10	7
CNC- RPFW 0.5	400	210		640	1170		0.5	4.31	3.7
CNC- RPFW 1	400	210		640	1170		1	4.31	3.5
CNC- RPFW 1.5	400	210		640	1170		1.5	4.31	3.5
CNC- Mec15	320	210	60	640	1170			2.31	8
CNC- Mec15- RPFW 0.5	320	210	60	640	1170		0.5	4.31	3.20
CNC- Mec15- RPFW 1	320	210	60	640	1170		1	4.31	3.4
CNC- Mec15- RPFW 1.5	320	210	60	640	1170		1.5	4.31	3.8
CRC50	400	210		640	585	585		2.25	6.7
CRC50- RPFW 0.5	400	210		640	585	585	0.5	4.42	3.5
CRC50- RPFW 1	400	210		640	585	585	1	4.40	3.10
CRC50-RPFW 1.5	400	210		640	585	585	1.5	4.40	3.4
CRC50- Mec15	320	210	60	640	585	585		2.15	7.2
CRC50- Mec15- RPFW 0.5	320	210	60	640	585	585	0.5	4.45	3.5
CRC50- Mec15- RPFW 1	320	210	60	640	585	585	1	4.43	2.9
CRC50- Mec15- RPFW 1.5	320	210	60	640	585	585	1.5	4.42	3.7

CNC: Control Concrete with 100% NCA.
CNC- RPFW 0.5: Control Concrete with100% NCA, 0.5% of recycled plastic fiber waste.
CNC- Mec15: Control Concrete with 100% NCA ,15% of Metakaolin.
CNC- Mec15- RPFW 0.5: Control Concrete with 100% NCA,15% of Metakaolin, 0.5% of recycled plastic fiber waste.
CRC50: Concrete with 50% RCA.

III. Discussion

III.1.Compressive strength

Natural granular concrete mixes based on plastic fibers (CNC-RPFW0.5, CNC-RPFW1) show a slight improvement in compressive strength at all curing ages (see figure.1). At 90 days of treatment, a rate of gain of 2.57% and 15% is observed respectively compared to the reference mixture. A 15% mass substitution of metakaolin did not affect the compressive strength except at a late age (90 days) when a small improvement is observed, that is to say a rate of gain of 11% compared to the control (CNC). When the two residues are used simultaneously (metakaolin and plastic fibers) the mechanical resistance remained almost the same for all composites without metakaolin except at 90 days of cure, the optimal mixture (CNC-Mec15- RPFW 1) shows a gain of 12% compared to the control concrete. The additional production of calcium silicate hydrate (C-S-H) gel at advanced stages sets in motion a pozzolanic phenomenon inducing internal hardening.

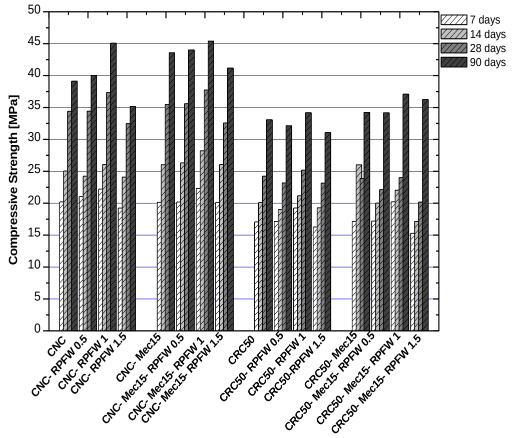

Figure 1. Compressive strength tests results of concretes

According to O'Farrell et al. [30], silicates react with calcium hydroxide (CH), producing a refinement of the pore structure, leading to an increase in resistance at late ages. The compressive strength of mixtures with recycled aggregates and those with plastic fibers (CRC50, CRC50-RPFW0.5, CRC50-RPFW1, CRC50-RPFW1.5) decreases for all ages, i.e. reduction rates of 15%, 13 %, 21% respectively at 90 days of treatment. When the three residues are used simultaneously an improvement is observed at an advanced stage of curing, the threshold is always marked at 1% fiber. This behavior has also been observed in concrete mixes that use tailings containing silica with RA [31]. Ge et al. [32] noticed that a significant amount of water is absorbed by the reactive silica powder during the pre-wetting time. As the relative humidity decreases with the hydration of the cement, this powder releases the absorbed water, aiding in the hydration of the cement and improving the strength at later ages. The high absorption values of recycled aggregates amplify this effect in samples that contain both residues.

III.2. Flexural strength

The behavior of all mixtures with respect to flexural strength is approximately similar to that of compressive strength. The addition of metakaolin to natural concrete and recycled concrete also affects the development of flexural strength at 90 days of cure, in particular the effect of reactive silica with calcium hydroxide released during hydration of the cement (see figure.2).

The simultaneous addition of metakaolin and plastic fibers to recycled concrete relatively increases the flexural strength compared to control concrete. The weakness of recycled aggregates in concrete is compensated by the addition of metakaolin, this is supported by some research [33,34]. The reduction rate of the optimal mixture (CRC50-RPFW1) is 22% compared to the control concrete and that of (CRC50-Mec15-RPFW1) is 19%.

The silica powder provided by the méakaolin contributed to the increase the flexural strength of this mixture.

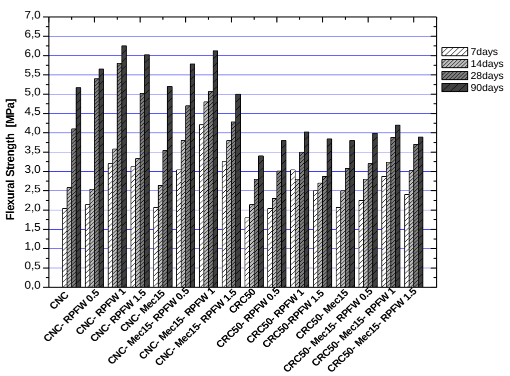

Figure 2. Flexural strength tests results of concretes

III.3. Impact energy

Natural concretes and those recycled without metakaolin and plastic fibers (CNC, CNC-Mec15, CRC50, CRC50-Mec15) exhibit brittle behavior, the energy absorbed at the first crack is slightly lower than that at failure (see figure.3).

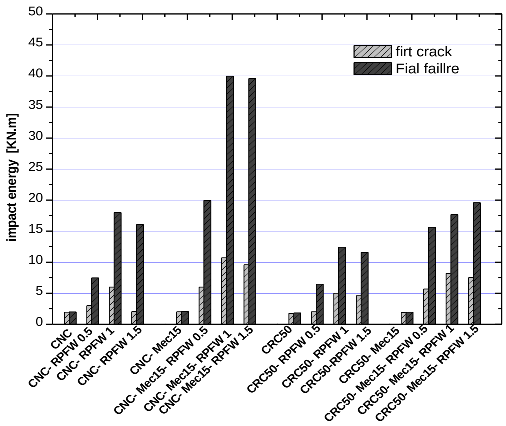

Figure 3. Impact energy tests results of concretes

The presence of metakaolin did not affect the impact strength of the mixtures (CNC, CNC-Mec15). On the other hand, the energy at break of the mixtures (CRC50, CRC50-Mec15) is 8%, 2% lower respectively than the control mixture, i.e. an influence of 6% of metakaolin in recycled concrete. When plastic fiber straws are used in these mixtures, their behavior has become ductile and the energy at break is significantly higher than that of the first crack and the effect of the reactive powder of metakaolin is too marked for all mixtures. The maximum energy at break which is equal to 39.98 KN.m was observed in the composite (CNC-Mec15- RPFW 1) compared to that of the control concrete which is 1.98 KN.m. The energy at the first crack is not affected for recycled concrete based on plastic fibers without metakaolin, but that at failure is significantly increased for this last composite compared to the reference concrete. When metakaolin powder is added to recycled concrete made from plastic fibers, a considerable evolution of the two types of energy is observed in these mixtures. The rates of increase of the energy at break of the mixtures (CRC50-Mec15- RPFW1.5, CRC50-Mec15-RPFW1, CRC50-Mec15- RPFW0.5) are respectively 888%, 791% and 688% compared to the control mixture (CNC).

V. Conclusion

In this research, the main experimental results on the mechanical properties and those of impact resistance of the concretes of natural aggregates and those recycled containing plastic fiber straws, metakaolin, and their combination are illustrated below.

Natural granular concrete mixes based on plastic fibers (CNC-RPFW0.5, CNC-RPFW1) show a slight improvement in compressive and flexural strength at all curing age.

- A 15% mass substitution of metakaolin did not affect the compressive and flexural strength except at a late age (90 days) when a small improvement is observed compared to the control (CNC).
- When the two residues are used simultaneously (metakaolin and plastic fibers) the mechanical resistance has remained almost the same for all composites without metakaolin except at 90 days of cure, there is an improvement. The optimal dosage of plastic fibers is always 1%.
- When plastic fiber straws are used in these mixtures, their behavior has become ductile and the energy at break is significantly higher than that of the first crack and the effect of the reactive powder of metakaolin is too marked for all mixtures.

VI. Field of application

The recycling of demolition materials meets the concerns of preserving or saving natural aggregates for the needs of operating sites. The use of plastic fiber straw waste compensates for the weaknesses of recycled aggregates and reduces the consumption of steels by increasing the ductility of concrete.

References

[1] Akhtar, A., Sarmah, A.K., 2018. Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective. J. Clean. Prod. 186, 262-281. https://doi.org/10.1016/j.jclepro.2018.03.085

[2] Zheng, C., Lou, C., Du, G., Li, X., Liu, Z., Li, L., 2018. Mechanical properties of recycled concrete with demolished waste concrete aggregate and clay brick aggregate. Results Phys. 9, 1317e1322. https://doi.org/10.1016/j.rinp.2018.04.061.

[3] Verian, K.P., Ashraf, W., Cao, Y., 2018. Properties of recycled concrete aggregate and their influence in new concrete production. Resour. Conserv. Recycl. 133, 30e49. https://doi.org/10.1016/j.resconrec.2018.02.005

[4] Brito, J., Agrela, F., 2019. New Trends in Eco-Efficient and Recycled Concrete. Woodhead Publishing pp1-3.

[5] Tunc, E.T., 2019. Recycling of marble waste: a review based on strength of concrete containing marble waste. J. Environ. Manag. 231, 86e97. https://doi.org/10.1016/j.jenvman.2018.10.034.

[6] Jiang, Y., Ling, T.C., Mo, K.H., Shi, C., 2019. A critical review of waste glass powder- Multiple roles of utilization in cement-based materials and construction products. J. Environ. Manag. 242, 440e449. https://doi.org/10.1016/j.jenvman.2019.04.098

[7] Afroz, M., Jobaer, M., and Hasan, M., "Performance of plain PET fibers to enhance the mechanical behavior of concrete under tension and shear" International Journal of Science, Engineering and Technology Research (IJSETR).2(9). 1668-1672. September. 2013.

[8]Soroushian, P., Plasencia, J.,and,Ravanbakhsh, S., "Assessment of reinforcing effects of recycled plastic and paper in concrete" ACI Material Journal. 100 (3). 203-207. 2003.

[9] P. Ganesh Prabhu, C. Arun Kumar, R. Pandiyaraj, P. Rajsh and L. Sasikumar, "Study on utilization of waste PET bottles fiber in concrete". International Journal of Research in Engineering & Technology. 2(5). 233-240. May 2014.

[10] Corinaldesi V, Moriconi G. Influence of mineral additions on the performance of 100% recycled aggregate concrete. Constr. Build. Mater. 2009;23:2869–2876.

[11] Etxeberria M, Vázquez E, Marí A, et al. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem. Concr. Res. 2007;37:735–742.

[12] Kou SC, Poon CS, Agrela F. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. Cem.Concr.Compos. 2011;33:788–795.

[13] Topçu IB, Şengel S. Properties of concretes produced with waste concrete 2004;34:1307–1312.

[14] Topçu IB. Physical and mechanical properties of concretes produced with waste concrete. Cem. Concr. Res. 1997;27:1817–1823.

[15] Ahmed SFU. Properties of concrete containing construction and demolition wastes and fly ash. J. Mater. Civ. Eng. 2013;25:1864–1870.

[16] Ahmed SFU. Existence of dividing strength in concrete containing recycled coarse aggregate. J. Mater. Civ. Eng.

[17] Shaikh FUA, Than AB, Odoh H. Effect of nano silica on properties of concretes containing recycled coarse aggregates.Constr.Mater.2014;168:68–76. doi:10.1680/coma.14.00009

[18] Shaikh FUA, Kerai S, Kerai S. Effect of micro silica on mechanical and durability properties of high volume fly ash recycled aggregate concrete (HVFARAC). Adv. Concr. Constr. 2015;3:317–332.

[19] Shaikh FUA. Effect of ultrafine fly ash on properties of concretes containing construction and demolition wastes as coarse aggregates. Struct. Concr. 2015;17:116–122. doi:10.1002/suco.201500030.

[20] Rao MC, Bhattacharyya SK, Barai SV.Behaviour of recycled aggregate concrete under drop weight impact load. Constr. Build. Mater. 2011;25:69–80.

[21] Bravo, M., De Brito, J., Pontes, J., and Evangelista, L. 2015. Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants. J. Clean. Prod. 99, 59–74.

[22] Mukharjee, B.B. and Barai, S. V. 2014. Influence of Nano-Silica on the properties of recycled aggregate concrete. Constr. Build. Mater. 55, 29–37.

[23] Kou, S.C., Poon, C.S.and Agrela, F. 2011. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. Cem. Concr. Compos. 33, 788–795.

[24] Siddique, R. and Klaus, J. 2009. Influence of metakaolin on the properties of mortar and concrete: A review. Appl. Clay Sci.

[25] Radonjanin, V., Malešev, M., Marinković, S.and Al Malty, A.E.S. 2013. Green recycled aggregate concrete. Constr. Build. Mater. 47, 1503–1511.

[26] Singh, N.and Singh, S.P. 2016. Carbonation and electrical resistance of self-compacting concrete made with recycled concrete aggregates and metakaolin. Constr. Build. Mater. 121, 400–409.

[27] Kou, S.C., Poon, C.S.and Agrela, F. 2011. Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures. Cem. Concr. Compos. 33, 788–795.

[28] Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L.and Arabi, N. 2013. Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. J. Clean. Prod. 54, 282–288.

[29] ACI Committee 544. State-of-the-art report on fibers reinforced concrete. ACI Committee 544 report 544.1R-96. Detroit (MI): American Concrete Institute; 1996.

[30] O'Farrell, M.; Wild, S.; Sabir, B.B. Pore size distribution and compressive strength of waste clay brick mortar. Cem. Concr. Compos. 2001, 23, 81–91.

[31] Nassar, R.-U.-D.; Soroushian, P. Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. Constr. Build. Mater. 2012, 29, 368–377.

[32] Ge, Z.;Wang, Y.; Sun, R.;Wu, X.; Guan, Y. Influence of ground waste clay brick on properties of fresh and hardened concrete. Constr. Build. Mater. 2015, 98, 128–136.

[33] Lee, G.C.; Choi, H.B. Study on interfacial transition zone properties of recycled aggregate by micro-hardness test. Constr. Build. Mater. 2013, 40, 455–460.

[34] Ismail, S.; Ramli, M. Mechanical strength and drying shrinkage properties of concrete containing treated coarse recycled concrete aggregates. Constr. Build. Mater. 2014, 68, 726–739.