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Optimal Allowable Residual Mortar Content in Recycled Aggregates Crushed from Parent Concrete Implementing Different Waste Materials

Iqbal Marie

Civil Engineering Department, Faculty of Engineering, The Hashemite University, Zarka, Jordan

Email address

iqbal@hu.edu.jo

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Abstract: The reuse of certain industrial and construction waste materials as a substitute to certain conventional materials in concrete mixtures will diminish the environmental problems that may be generated by diverting these materials to the landfill in addition to the conservation of raw materials. However, using concrete having waste materials (parent concrete) to produce recycled aggregates and to substitute partially natural aggregates, will adversely affects the quality of the new concrete. The type of waste material in the parent concrete and the adhered mortar attached to the natural aggregate particles are main factors affecting the obtained concrete quality. Therefore, this study has focused on detecting the acceptable amount of adhered mortar on the recycled aggregates without significantly affecting concrete properties. The ultrasonic pulse velocity has been implemented as an indication of concrete quality. The results showed that the type and the amount of the old residual mortar content (RMC) have significant effect on the behaviour of ultrasonic pulses in concrete, and hence on its strength. The results indicate that 10% RMC will have accepted reduction in concrete strength.

Keywords: Recycled Aggregate, Ultrasonic Test, Non-destructive Testing, Residual Mortar Content, Parent Concrete

1. Introduction

Several kinds of waste materials may be used as substitute for conventional materials in concrete mixes and be a solution to minimize the growth of certain non-decaying waste materials that harm the environment. In particular, this study will focus on scrap tires, demolished concrete, glass and plastics wastes. The construction activities may be directed to be environmental friendly by the use of this kind of waste materials in construction field applications such as partial substitute for natural aggregates, in its coarse and fine form, in concrete mixes. This application will reduce the volume of waste materials that were dumped in landfills. The environmental and economic advantages that occur when waste materials are diverted from landfills comprise: a. conservation and efficient use of raw materials; b. reduction in disposal coast; d. reduction in the environmental problems created by dumping these materials.

The old crushed concrete that comprises some kind of waste materials that may be used to produce recycled concrete aggregates is known as parent concrete. The parent concrete may itself be using recycled aggregates thus going through a second loop of recycling following a cradle to cradle life cycle [1].

The physical properties of aggregates are affected substantially by their origin, shape, size and surface texture [2], [3]. Since the total solid volume of concrete is composed of 70 to over 80 present of aggregate [4], therefore the engineering properties of concrete implementing recycled concrete aggregate (RCA) in its composition will be affected. Accordingly, it is of great interest to evaluate the properties of concrete that uses recycled aggregates of different kinds of waste materials in its composition. The ultrasonic pulse velocity (UPV) techniques will be used to understand the influence that these aggregates have on the strength of concrete and how such effects can be minimized by reducing the amount of the residual old mortar content (RMC). This technique is one of the most prevalent non-destructive techniques used to assess concrete quality and to evaluate some of its properties. However, it does not accurately estimate the concrete compressive strength since the UPV values are influenced by factors, which do not necessarily affect the concrete compressive strength by the same degree [5].

Several researches were conducted to evaluate the reliability of UPV method as a non-destructive technique (NDT) for determining the compressive strength of concrete. UPV increases considerably by increasing the size and amount of coarse aggregates. The type as well as the density of aggregate has also a large impact on the UPV [6]. Accordingly, aggregate percentage, aggregate maximum size and aggregate origin have a great influence on concrete matrix properties and therefore on the UPV results.

This investigation focuses on the application of ultrasonic, non-destructive, testing for assessing the effect of the percentage and origin of RMC present in the composition of the recycled aggregate. The origin of RCA varies according to the parent concrete. Different types of parent concretes will be used that were incorporating different kinds of wastes such as crushed glass, plastic particles, crump rubber and recycled concrete aggregates and relate the results to the strength of concrete. This investigatory approach has not been used for quantifying the allowable amount of RMC in the literature so far.

2. Experimental Program

An experimental program was developed to investigate the effect of the percentage of the RMC, available on the recycled aggregates, on the behaviour of UPV in concrete and consequently on its compressive strength. The allowable RMC percentage for minimal effect on concrete properties will also be investigated.

Different parent concrete mixtures which have been used in this study as sources of RCA were prepared in the lab using different waste materials as partial replacement to coarse or fine aggregates. The ratio of replacement was kept to 20% for all types of waste materials used; rubber, plastic and glass [7], [8]. After 28 days curing the prepared parent concretes were crushed manually with hand hammer and then crushed using Los Angeles (LA) abrasion machine to minimize the RMC. Many different methods were used by researchers to reduce the attached old mortar content on the surfaces of RCA. Ismail & Ramli [10] found that minimization of RMC will significantly enhance the mechanical and physical properties of the RCA.

Three levels of crushing were used to obtain three types of recycled aggregates of different amount of RMC for each parent concrete. New concrete mixtures were prepared by replacing a predetermined amount, (20%), of the natural coarse aggregates by the prepared crushed waste recycled coarse aggregates. Natural local lime stone coarse aggregates (NA) also used to obtain reference concrete for comparison.

An experimental work progress methodology flow chart is shown in figure 1.

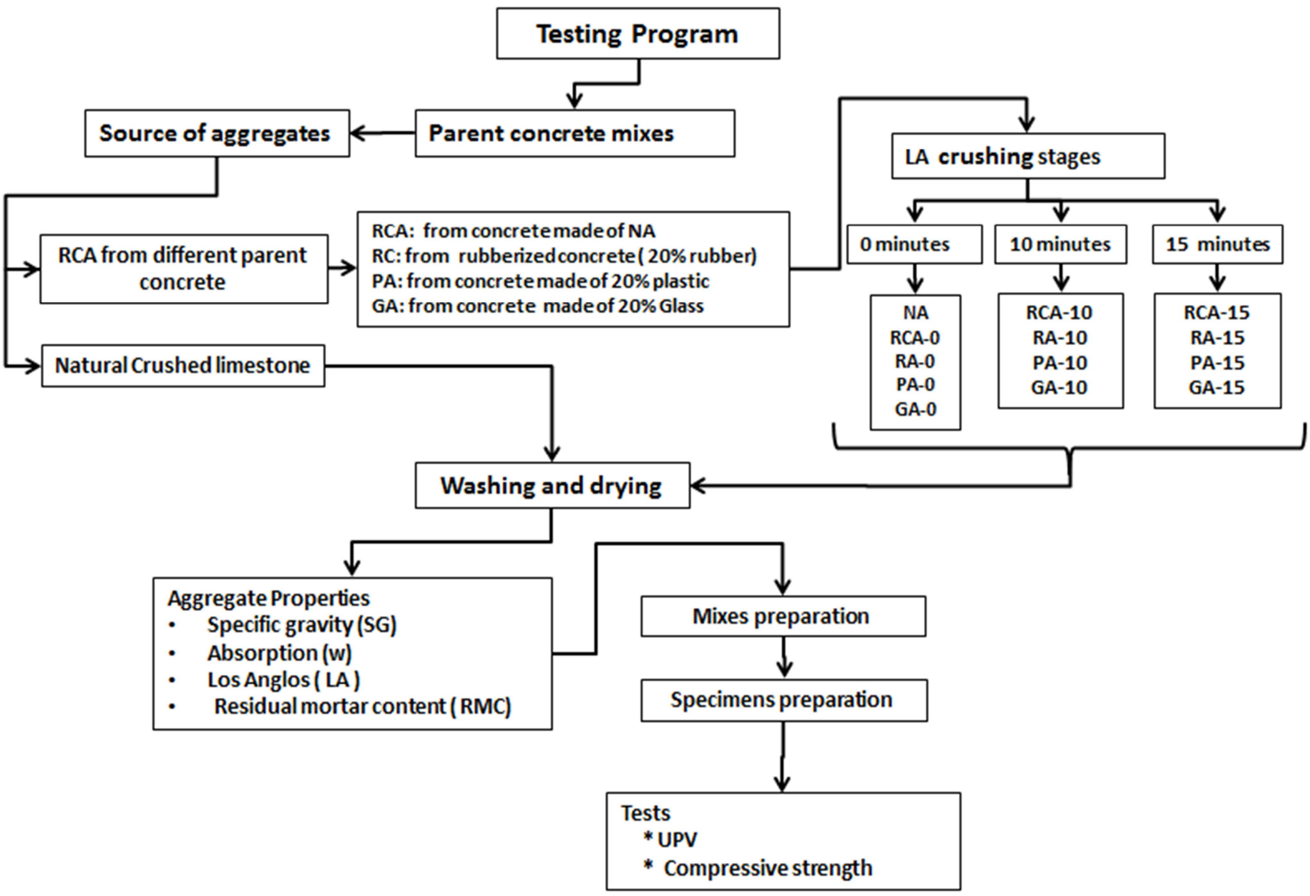


Figure 1. An experimental work progress methodology flow chart for aggregates preparation and testing.

2.1. Materials

Four different types of RCA were used in this study in addition to the natural crushed limestone which is provided by a local aggregate supplier. The four types of RCA are; recycled aggregates that were produced by crushing pre-prepared concrete laboratory samples of different concrete mixtures having different waste materials in their composition.

The parent concrete mixtures are:

1. Concrete mixture having 100% NA,
2. Rubberized concrete having crumb rubber replacing 20% of natural fine aggregate,
3. Concrete having glass partially replacing 20% of fine aggregates. The glass was manually crushed in the laboratory and then sieved,
4. Concrete having plastic partially replacing 20% of fine aggregates.

The waste materials that were used as replacement to natural sand in parent concrete mixtures are shown in figure 2.

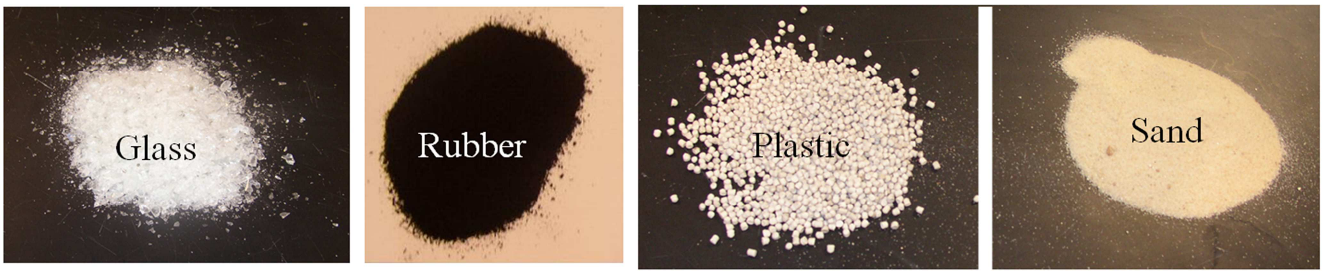


Figure 2. *Waste materials used to replace natural sand in parent concrete mixtures.*

The percentage of waste materials was limited to 20% in all parent mixes since compressive strength of concrete using recycled aggregates in its composition is adversely influenced by the properties and the amount of recycled aggregate [1], [7]. The gradation curves for crumb rubber, plastic, glass and natural sand are shown in figure 3. The particle size distribution for each kind of waste material particles showed to be within the accepted standard limits. Table 1 shows the assigned label for each type of concrete mixture according to the type of recycled aggregate used in its composition.

Gradation of the coarse NA aggregates and all other types of recycled concrete aggregates were obtained using ASTM C136. The maximum nominal size of coarse aggregate is 20 mm. The particle size distribution curves are shown in figure 4.

Table 1. *Concrete labels according to the waste material used in the parent concrete.*

Concrete mix ID.	Waste used in parent concrete	Recycled aggregate ID	% replacement of RCA in the new concrete
M-NA	Limestone NA	NA	0
M-RCA	Recycled concrete	RCA	20%
M-RA	Crumb rubber	RA	20%
M-PA	Plastic	PA	20%
M-GA	Glass	GA	20%

All types of recycled aggregates were obtained by manual crushing the prepared parent concrete samples into smaller particles using a steel hammer, then were subjected to further crushing using the LA machine. Three crushing time periods were used to obtain different percentages of RMC. The three periods are: 0, 10 and 15 minutes on the LA machine. Some of the physical and mechanical properties of the recycled coarse aggregates obtained from each crushing stage for each type of parent concrete are listed in table 2. The assigned number in the ID of each type of aggregates represents the crushing stage.

Table 2. *Physical and mechanical properties of all types of recycled coarse aggregates.*

Aggregate Type	NA	RCA			RA			PA			GA		
		RCA 0	RCA 10	RCA 15	RA 0	RA 10	RA 15	PA 0	PA 10	PA 15	GA 0	GA 10	GA 15
Specific gravity	2.64	2.35	2.45	2.5	2.2	2.4	2.5	2.2	23	2.45	2.3	2.45	2.55
Water absorption (%)	0.92	8.93	6.6	5.2	9.3	8.0	6.5	10.4	9	7	10.2	8	6.5
LA abrasion (%)	24.6	32	30	27	37	35	32	41	37	34	38	35	31

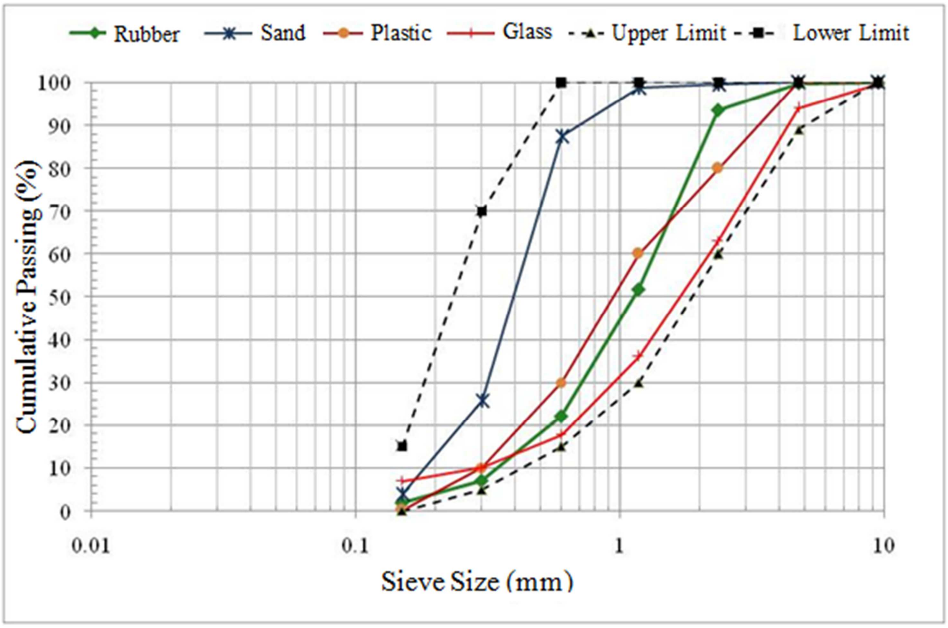


Figure 3. *Cumulative percentage passing versus the logarithmic sieve size for sand and all types of waste materials within the standard upper and lower limits.*

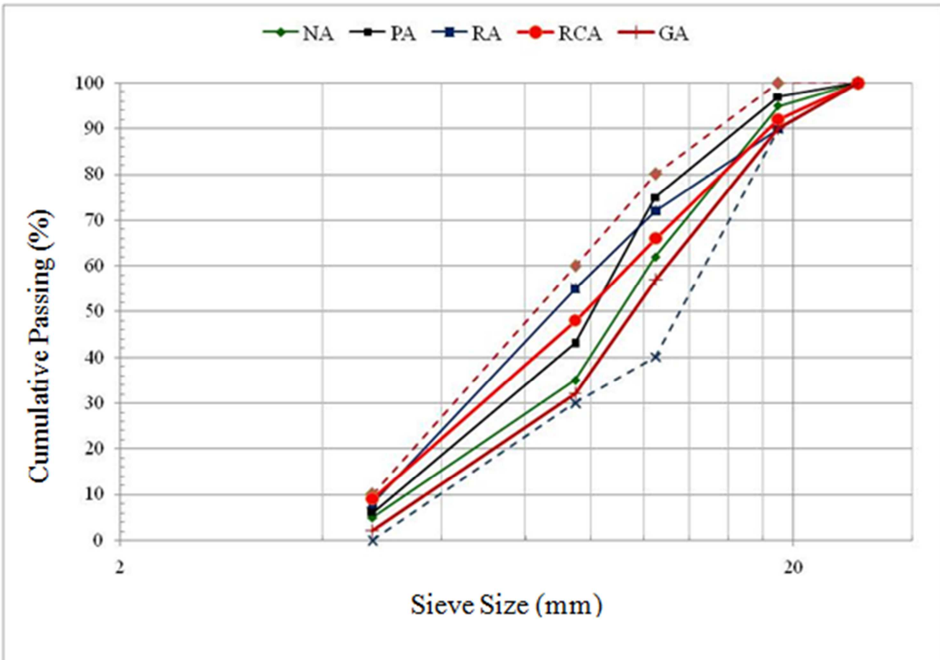


Figure 4. *Cumulative percentage passing versus the logarithmic sieve size for coarse NA and all types of RCA within the standard limits.*

2.2. Residual Mortar Content (RMC)

Recycled concrete aggregates consist of attached mortar portion remained after crushing the base parent concrete in addition to the natural coarse aggregate or from the parent concrete mortar. Hence, the properties of the recycled aggregates are directly related to the type and properties of the parent concrete. The RMC was determined by researchers using different methods [9]. The thermal treatment method is used in this study to disintegrate the attached mortar from the surface of the NA. The prepared aggregates were soaked in water for 24 hours. Followed by heating to a temperature of 400°C for a period of two hours. After heating, the aggregate samples were suddenly cooled by immersing them in cold water. The sudden reduction in the aggregate temperature generates internal thermal stresses that cause the adhered old mortar to become very brittle. Consequently, it will easily be detached manually by rubber hammer blows. Through visual inspection, all the particles were checked to assure 100% removal of old adhered mortar [11], [12]. This has been repeated for each type of recycled aggregates after each stage of crushing. The percentage of RMC can be calculated as follows:

$$\text{RMC (\%)} = \frac{Mass\ of\ RCA - Mass\ of\ RCA\, after\ mortar\ removal}{Mass\ of\ RCA} x100$$

The results were tabulated in table 3.

Table 3. *RMC (%) for each type of aggregates after each crushing stage.*

Aggregate Type	NA	RCA			RA			PA			GA		
		RCA 0	RCA 10	RCA 15	RA 0	RA 10	RA 15	PA 0	PA 10	PA 15	GA 0	GA 10	GA 15
Crushing time (minutes)	-	0	10	15	0	10	15	0	10	15	0	10	15
RMC (%)	0	16	14	12	24	16	9	23	13	7	25	18	8

2.3. Concrete Mixes

Concrete mixes were prepared using the prepared different types of recycled aggregates, replacing 20% of natural coarse aggregates. The mix proportions are shown in table 4. As well the air content percentage and the unit weight for each concrete mix are listed in table 4. All mixes have same W/C ratio, curing conditions, and compaction procedure.

Three concrete cubes of 150 x 150x 150 mm dimensions were prepared from each concrete mix. All specimens were cured after mould removal in a water bath at 23° C ± 2°C for 28 days in accordance with ASTM C192.

Table 4. *Concrete mixtures proportions and their fresh properties.*

Mix ID	Mix proportions (kg/m^3) of finished concrete)								W/C	Air content (%)	Unit weight Kg/m^3
	Water	Cement	C.A*	F.A*	RA*	PA*	GA*	RCA*			
M-NA	252	446	961	585					0.56	1.70	2389
M-RCA-0										2.10	2272
M-RCA-10	252	446	768.8	585				192.2	0.56	1.97	2290
M-RCA-15										1.82	2300
M-RA-0										3.15	2217
M-RC-10	252	446	768.8	585	192.2				0.56	2.9	2230
M-RC-15										2.48	2286
M-PA-0										4.00	2249
M-PA-10	252	446	768.8	585		192.2			0.56	2.43	2250
M-PA-15										2.36	2276
M-GA-0										2.81	2300
M-GA-10	252	446	768.8	585			192.2		0.56	2.67	2365
M-GA-15										2.31	2370

*C.A: Coarse Aggregates
*F.A: Fine Aggregates
* RCA: Recycled Coarse Aggregates
*RA: Rubberized aggregates
* PA: Plastic aggregates
* GA glass aggregates

2.4. UPV Testing

Several experimental setup arrangements can be used for UPV measurements: direct, semi-direct or indirect. Indirect measurements can be affected by the surface conditions [6]. Therefore, the UPV measurements were conducted using the direct arrangement, direct transmission through concrete, according to ASTM C597. The transducers firmly held onto opposite faces of the concrete specimens, at the age of 28 days, using petroleum jelly as shown in figure 5. The transmission time that an ultrasonic pulse takes to pass through a known distance of concrete, cube length, between a transmitter and a receiver was recorded in microseconds (µs). The UPV in (m/s) was calculated by dividing the path length by the transit time [13]. The transducers used are having 54 kHz frequency. Three cubes from each different mixes were tested. The time was measured for three pairs of opposite faces of each cube after being cleaned and prepared for testing. The cubes were kept in position and were maintained stable during testing by the use of the compression-testing machine to apply a very negligible load on the tested cube. The direct experimental set up arrangement for the direct UPV test is shown in figure 5. The average time for the pulse to propagate through the length of the cube was recorded. Then the velocity of transmission of the UPV was calculated and recorded in table 5. The load was then applied at a constant rate of 0.5 MPa/sec until failure. The tests were conducted for all specimens under the lab environment at temperature of 25 ± 2°C. The temperature influence on the results is negligible between 0°C and 30°C [6]. The RMC, UPV and ultimate compressive strength were recorded in table 5 for each type of concrete mixes.

Table 5. *The RMC in each recycled aggregate, the UPV and compressive strength for each concrete mix.*

Aggregate Type	NA	RCA			RA			PA			GA		
		RCA 0	**RCA 10**	**RCA 15**	**RA 0**	**RA 10**	**RA 15**	**PA 0**	**PA 10**	**PA 15**	**GA 0**	**GA 10**	**GA 15**
Crushing time (minutes)	-	0	10	15	0	10	15	0	10	15	0	10	15
RMC (%)	0	25	20	12	23.5	16	9	23	13	7	24	18	11
Concrete mix	M-NA	M-RCA-0	M-RCA-10	M-RCA-15	M-RA-0	M-RA-10	M-RA-15	M-PA-0	M-PA-10	M-PA-15	M-GA-0	M-GA-10	M-GA-15
UPV(m/sec)	2700	2300	2400	2600	2200	2300	2500	2180	2250	2440	2220	2300	2500
Compressive strength (MPa)	35	27	28.5	31	25	27	30	20	22	26	31	32	34

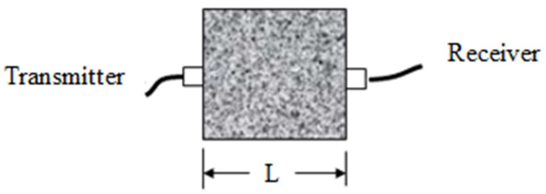


Figure 5. *Direct ultrasonic pulse velocity test arrangement.*

3. Results and Discussion

The influence of the attached mortar content on the properties of RCA was studied by de Juan & Gutiérrez [12]. The adhered mortar content adversely influences RCA properties due to the presence of several cracks and due to its porous nature that is not present in NA [15]. If the attached mortar contains waste materials, then an additional decrease in the concrete quality will take place. The crushing process has influence on the amount of detrimental RMC. The reduction percentage in RMC depends on the type of parent concrete which is found to be higher for PA. That means recycled concrete aggregates obtained from parent concrete having waste plastic in its composition is of the lowest quality. The reduction in RMC for each type of recycled aggregates that took place due to the second and third crushing stages relative to the first crushing stage, is shown in figure 6.

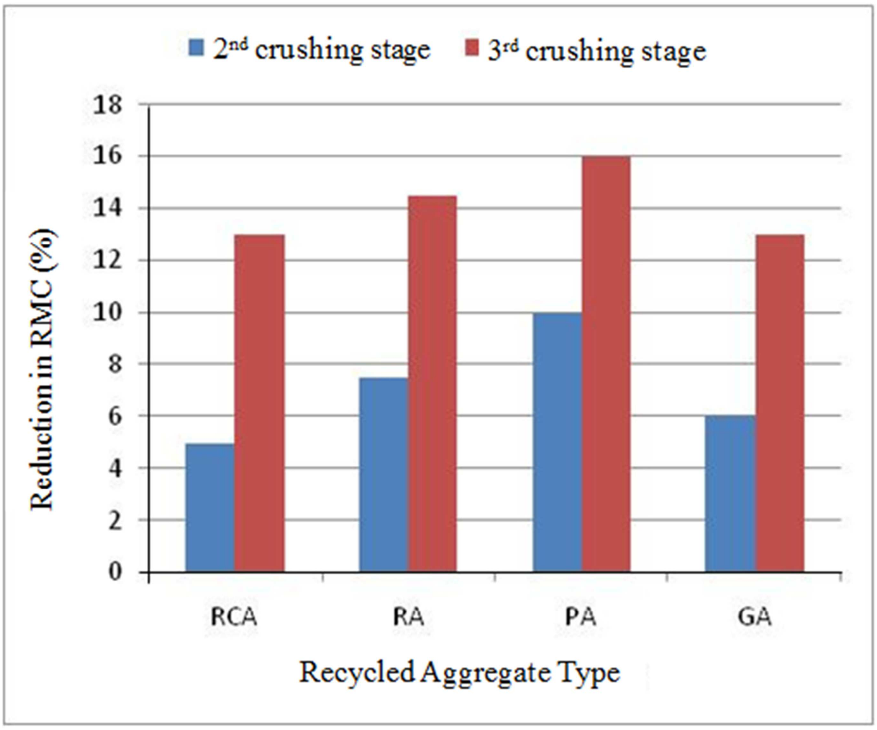
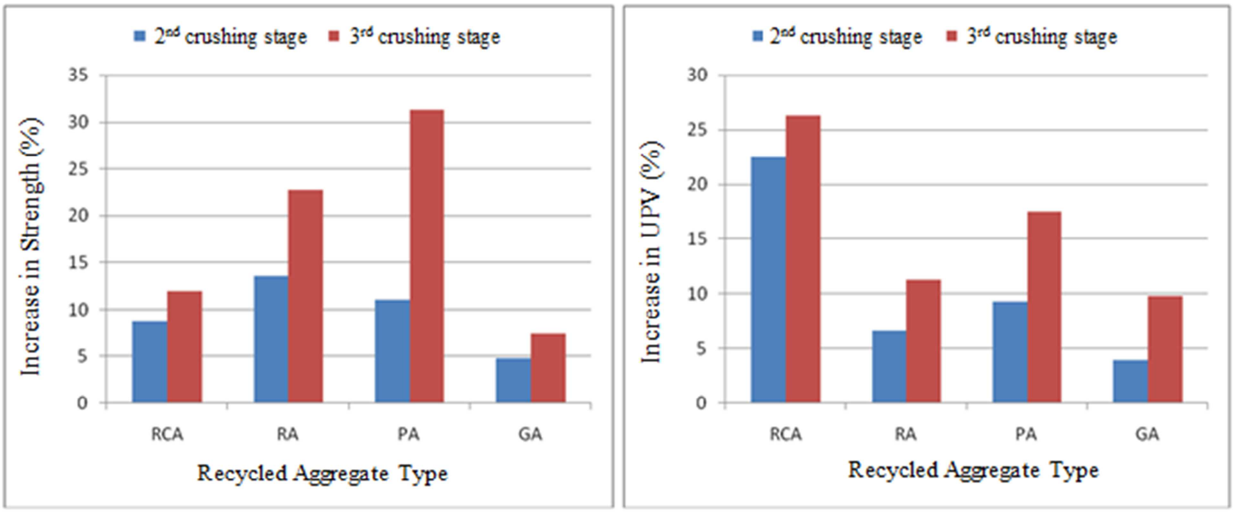


Figure 6. *The percentage reduction of RMC for each type of recycled aggregates.*

Mortar is less dense than NA irrespective of the parent concrete, therefore the more adhered cement mortar at the surface of the recycled aggregates, the lower the specific gravity. Henceforth, an increase in the UPV is noticed for each crushing stage. The percentage increase in the UPV for each crushing stage is shown in figure 7-a. The reduction in RMC also showed an increase in the compressive strength as it is clear from figure 7-b.

The UPV increases as the amount of RMC for all types of recycled aggregates decreases. This trend is due to the reduction in the porous adhered concrete parent mortar on the recycled aggregates. Although the LA machine was used to have different crushing stages, it is very clear that the crushing stage affects positively the recycled concrete aggregates quality irrespective of the parent concrete due to the successive breaking up of adhered cement mortar from the surface of the recycled aggregates.



a b

Figure 7. Effect of the amount RMC for each type of aggregates on: a. Compressive strength; b. UPV.

As far as the UPV values fall in the range of 3.5 km/s and 4.5 km/s, the specimens can be categorized as being in good condition which indicates that the concrete has no cracks or any large voids that may affect its structural integrity [16]. It is clear from figure 8 that the reduction in RMC increases the UPV for M-RCA from good to excellent condition. According to the suggested UPV rating for concrete by Malhotra & Carino (2004) [16]. Reducing the RMC to 11% or less in PA in M-PA may increase the quality of the concrete from doubtful condition to good condition. Concrete with RA or GA quality remains within the good condition state, however the UPV showed an increasing trend with decreasing RMC percentage and hence increase in their strength. If higher concrete strength is used with RA and GA the quality may increase to reach excellent conditions.

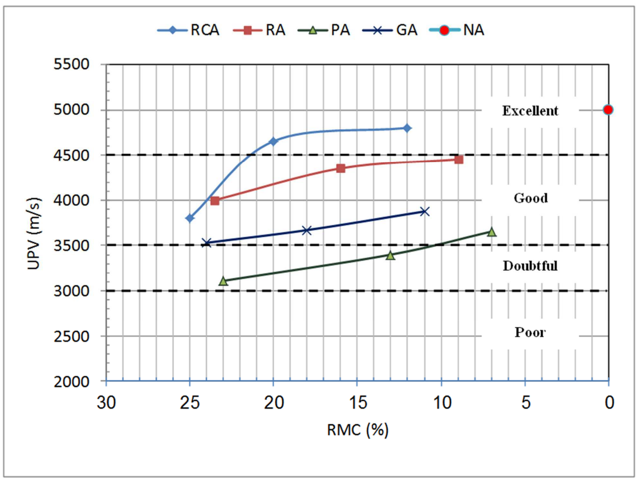


Figure 8. Relationship between the RMC percentage and the UPV within the boundaries of suggested UPV rating for concrete by Malhotra & Carino (2004).

Table 6 shows the increment in the compressive strength, percentage, for certain reduction in the RMC after a 15 minutes LA crushing time. M-PA concrete showed the highest reduction in RMC after 15 minutes of LA crushing time with an increase in compressive strength of about 31.3% relative to that of zero crushing time followed by M-RA that showed a 22.7% increment in strength.

Table 6. *The reduction in RMR percentage after 15 minutes crushing and the percentage increment in compressive strength of concrete samples.*

Type of RCA	RCA	RA	PA	GA
Crushing time (minutes)	15	15	15	15
Reduction in RMC%	13	14.5	16	13
Concrete mix	M-RCA	A-RA	M-PA	M-GA
Compressive strength increment (%)	12	22.7	31.3	7.4

4. Conclusion

This study focused on detecting the acceptable amount of adhered mortar on different types of RCA that have waste materials, in particular, scrap tires, demolished concrete, glass and plastics wastes, in its composition without significantly affecting the concrete properties.

The results showed that the type and the amount of the old RMC have significant effect on the behaviour of ultrasonic pulses in concrete, and hence on its strength. Therefore, the type and crushing process of the parent concrete affect the properties of the obtained recycled aggregates and hence the compressive strength of the concrete mix incorporating these RCA. However, it is detected that the optimal RMC in recycled concrete aggregates varies according to the type of waste in its composition. Moreover, the optimal RMC was found to be 10% which is acceptable and does not significantly reduce the compressive strength of concrete having recycled aggregates in its composition that were obtained from parent concrete incorporating rubber, glass, or plastic. Whereas, the accepted optimal RMC was found to be 25% for RCA obtained from parent concrete having natural aggregates in its composition, therefore less crushing is required for such type of parent concrete. Generally, to enhance the compressive strength of concrete mixtures incorporating RCA, it is advisable to reduce the amount of residual mortar attached at the surface of aggregate particles especially for recycled aggregates having plastics in its composition.

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