Recycled aggregate as structural material

A.A. Tsoumani [1], N.-M. Barkoula [1], T.E. Matikas [1],

[1]Department of Materials Science and Engineering, University of Ioannina, 45110 Ioannina, Greece
Presenting author email - tel.: anna.tsoumani@gmail.com - +302651026701

Abstract
The amount of construction and demolition waste has increased considerably over the last few years. The increasing cost of landfill, the scarcity of natural resources coupled with the increase in aggregate requirement for construction, has attracted increasing interest from the construction industry concerning the use of recycled aggregate (RA) to replace aggregate from natural sources. Low-grade applications, including sub-base and roadwork, have been implemented in many countries; however, higher-grade activities are rarely considered. This research examines whether the use of RA in concrete production is appropriate. The utilisation of RA in concrete opens a whole new range of possibilities in the reuse of materials in the building industry. In the context of this research, several aggregates' properties, which affect concrete's production, were tested using international standards. Thereafter, in order to determine whether the RA are suitable for use in the production of concrete, the results where compared with the requirements of the Greek standard ELOT 401 - the Greek regulation of concrete technology (1997) and the European standard EN12620. The tests' results, led us to the conclusion that fine RA should not be used due to their low quality, while coarse RA are not excluded from concrete production.

Keywords: construction and demolition waste, recycled aggregates, concrete, geometrical – physical properties

1. Introduction

Nowadays, construction and demolition (C&D) waste constitutes a major portion of the total solid waste production in the world. As construction wastes are classified wastes from the construction, remodeling and repairing of individual residences, commercial buildings and other civil engineering structures while as demolition wastes those from razed buildings. C&D wastes may be also produced significantly from environmental disasters, such as earthquakes, hurricanes, tornadoes, and floodwater [1]. Discarding waste without any pre-treatment provokes a considerable burden to the environment, which apart from soil and water contamination as well as air pollution, includes also aesthetic degradation, reduced property values and landscape destruction.

Preservation of the environment and conservation of the rapidly diminishing natural resources should be the essence of sustainable development. Continuous industrial development poses serious problems of C&D waste disposal, whereas on the one hand, there is critical shortage of natural aggregates for production of new concrete. One of the ways to solve this problem is to use this 'waste' as aggregates [2]. Modern technology offers valuable solutions to address to this problem. Recycling C&D wastes is a very common practice in many developed countries [1].

Research by concrete engineers has clearly suggested the possibility of appropriately treating and reusing such waste as aggregate. The studies have been going on for 50 years. In fact, none of the results showed that recycled aggregates (RA) are unsuitable for structural use. However, some hypothetical problems related to durability aspects resulted in recycled aggregates being employed practically only as base filler for road construction [3]. In the study presented herein, a number of tests have been carried out in order to confirm the possibility of using recycled aggregates in producing concrete.

2. Experimental

2.1 Material

The material used in this research was derived from a C&D waste recycling plant, administrating derivatives from excavations, construction, renovations, demolitions and other projects private or public, such as pavement and roadways' demolition, that is located in the industrial area of Thessaloniki, Greece. The origins of the C&D waste were unknown; therefore, the composition was evidently heterogeneous, depending on the type, age, use and size of the structure it came from.

The sample of C&D waste used as recycled aggregates contained: pieces of concrete, bricks, ceramic tiles, marble, asphalt and natural aggregates (sand, carved stones, gravel). Besides, it contained a small percentage of: mosaic, wood, plasterboard, plywood, pieces of plumbing parts, plastic parts, metal objects (wires, screws, etc.), cables, paper, dirt and other pollutants. The percentage of each material in our sample is presented in Figure 1, showing that the largest part obtained is concrete, as it is the most used construction material nowadays.

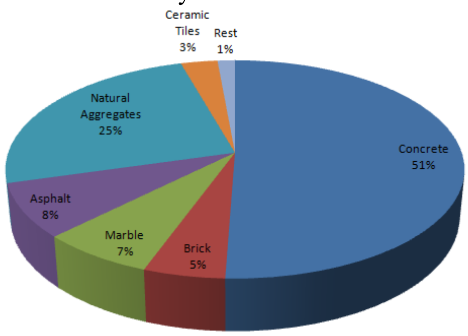

Figure 1 Construction and demolition waste composition.

The plants for production of RA are often not much different from that for crushed aggregates from rock. Figure 2 presents a panoramic photograph of the production plant and figure 3 illustrates the mechanical sorting process, consisting of six operation units. They include bar screening, trommel screening, disk screening, impact crusher, magnetic separation, air classification and final manual separation.

Figure 2 Production plant [4].

The C&D wastes are delivered to the facility site by trucks and dumped onto the floor. Bulky wastes such as rock, plastic, wood, steel, or concrete, are first sorted using a vibrating screen. Wastes, such as sand, soil, gravel, grain, or pebbles, smaller than the mesh size of the vibrating screen are passed through the first operation unit and sent into the horizontal trommel screen and impact crusher in sequence. Ferrous metals can be extracted from C&D wastes directly using an overhead magnetic separator. Recovered ferrous metals can be collected for material recycling, recovery and reuse. The air classifier further isolates inert materials, such as wood or plastic from the other available C&D wastes. Residual waste materials, passing through the air classifier, are sent into a manual sorting unit (pick station) for further separation. Products gathered from the manual separation process consist mainly of wood chips and other residues, such as scrap tires [4]. Via this process, recycled aggregates of four size fractions are produced: <5mm, 6–11mm, 12–25mm and 26–55mm.

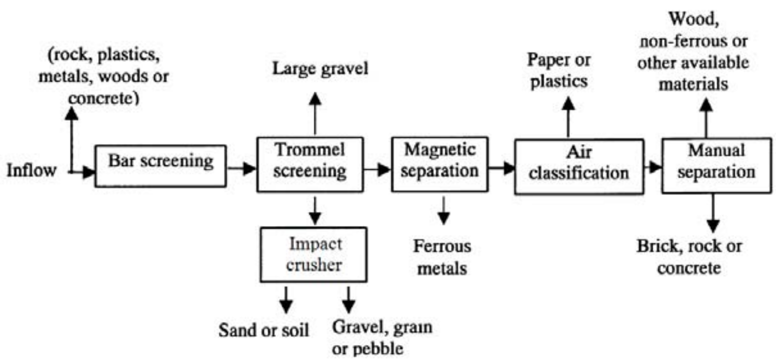

Figure 3 Mechanical sorting process.

2.2 Properties of recycled aggregates

Due to the variability in the composition of RA, it is essential to carefully study their properties. In the context of this research, the aggregates' properties that affect concrete's production were tested using international standards (ASTM - EN), as shown in Table 1. Particularly, the following geometric properties were determined: particle size distribution (sieving method), shape and texture, percentage of shells in coarse aggregates, percentage of fines and assessment of fines (methylene blue test and sand equivalent value) and the following physical properties: resistance to degradation by abrasion and impact (Los Angeles machine), specific gravity, water absorption and Sodium Sulfate Soundness Test Mass Loss. The geometric properties affect the composition and pumping of concrete, while physical properties affect the strength and durability of concrete.

		Property	Fine	Coarse	Standard
Geometrical	1	Particle size distribution (Sieve Analysis)	X	X	ASTM C136
	2	Determination of the amount of material finer than a 75-μm (No. 200) sieve in aggregate by washing.	X	X	ASTM C117
	3	Determination of particle shape — Flakiness index		X	EN 933 -3
	4	Determination of shell content - Percentage of shells in coarse aggregates		X	EN 933-7
	5	Sand Equivalent Value of Soils and Fine Aggregate	X		ASTM D2419
	6	Assessment of fines - Methylene blue test	X		EN 933 -9
Physical	5	Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine		X	ASTM C131
	6	Specific Gravity and Absorption of Fine Aggregate	X		ASTM C128
	7	Specific Gravity and Absorption of Coarse Aggregate		X	ASTM C127
	8	Soundness of Aggregate by Use of Sodium Sulfate	X	X	AASHTO T 104

Table 1 Aggregates' properties – corresponding Standard.

Thereafter, whether the RA are suitable for use in the production of concrete was determined by comparing the tests' results with the requirements of the Greek standard ELOT 401 - the Greek regulation of concrete technology (1997) and the European standard EN12620. Furthermore, the results were compared to the properties of natural aggregates and the expected properties of recycled aggregates based on international literature.

In this point, it is essential to mention that for each property a sample was collected according to the standard ASTM D75 so that the samples obtained would show the nature and condition of the materials which they represent. Furthermore, the samples were reduced to the appropriate size for testing, employing a technique that is described in the test ASTM C702: Method B – Quartering, described in Figure 4. In addition, the results of each test where the average of three independent measurements.

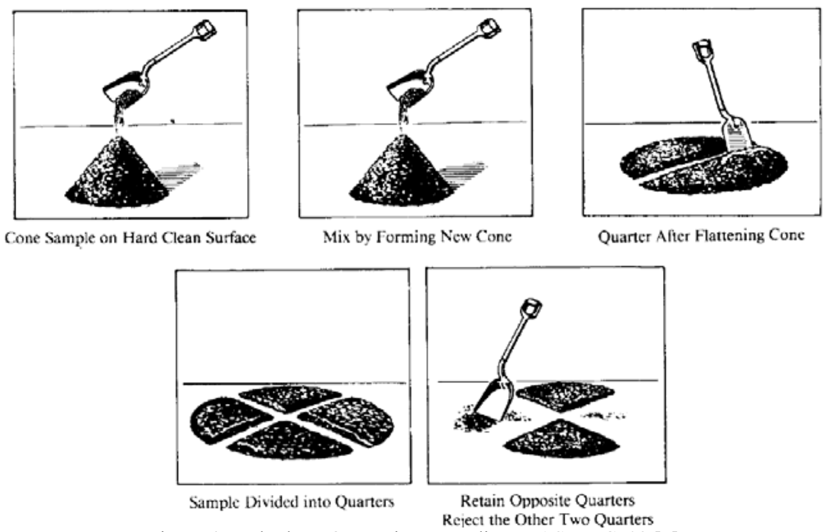

Figure 4 Method B - Quartering according to ASTM C702 [5].

3. Results and discussion

3.1 Grading of coarse and fine aggregates

Test method ASTM C136 was used to determinate the compliance of the particle size distribution of both coarse and fine aggregates with nominal size larger than 75-μm. This method included sieving a sample of aggregate with standard sieve frames that conformed to the requirements of specification ASTM E11. Accurate determination of material finer than the 75-μm (No. 200) sieve was achieved by washing, according to test Method C117. Table 2 presents the tests' results.

Sieve Designation ASTM E11	Sieve size (mm)	Recycled aggregates			
		Fine	Coarse		
			nominal size (mm)		
		0 - 5 mm	6 - 11 mm	12 - 25 mm	26 - 55mm
		% passing			
1 1/2"	38,1	100,00	100,00	100,00	100,00
1"	25,0	100,00	100,00	99,42	46,40
3/4"	19,0	100,00	100,00	82,75	35,02
1/2"	12,5	100,00	100,00	48,66	33,57
3/8"	9,50	100,00	98,92	26,07	33,18
No 4	4,75	99,44	40,05	11,43	32,10
No 8	2,36	74,16	16,20	10,32	31,78
No 16	1,18	52,90	15,30	9,68	31,54
No 30	0,60	37,84	14,62	9,01	31,26
No 50	0,30	24,83	13,77	8,07	30,83
No 60	0,25	22,59	13,55	7,84	30,71
No 200	0,075	14,08	11,54	6,34	30,03

Table 2 Sieve analysis of RA.

The possibility of using these aggregates as concrete aggregates was investigated at first by comparing their grading with the grading of natural aggregates (Table 3). Natural aggregates (NA) that are used for concrete production have a nominal size of lower than 25mm. As seen comparing Tables 2 and 3, RA have grading similar to natural ones.

Sieve Designation ASTM E11		Natural aggregates		
		Fine	Coarse	
			nominal size (mm)	
		0 - 5 mm	6 - 9,5 mm	10 - 25 mm
		% passing		
1 1/2"	38,1	100,00	100,00	100,00
1"	25,0	100,00	100,00	96,17
3/4"	19,0	100,00	100,00	65,15
1/2"	12,5	100,00	100,00	8,32
3/8"	9,50	100,00	93,20	3,34
No 4	4,75	99,99	36,10	2,08
No 8	2,36	86,96	2,50	1,74
No 16	1,18	53,35	1,50	1,53
No 30	0,60	33,38	1,40	1,48
No 50	0,30	22,36	1,40	1,39
No 60	0,25	20,57	1,30	1,37
No 200	0,075	13,47	1,30	1,24

Table 3 Sieve analysis of NA.

The possibility of using them in concrete production, was then investigated according to the requirements of the Greek standard ELOT 401 - the Greek regulation of concrete technology (1997). For this purpose, a theoretical concrete mix was formed, as ELOT-401 provides lower and upper limits only for aggregate mixtures. The theoretical mix was designated for reinforced concrete as this is the most common concrete use in Greece. The upper and lower limits are shown in Table 4 and Figure 5. Obviously, the aggregates' mix curve is within the limitations of ELOT-401 [6].

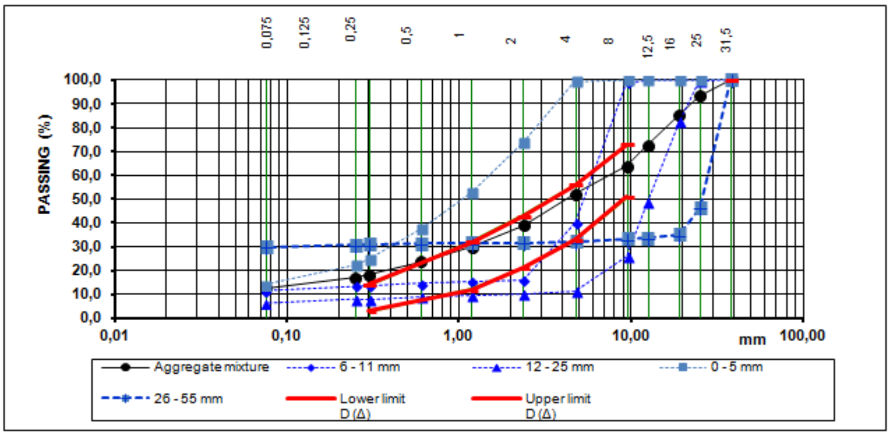

Figure 5 Theoretical aggregates' mix curve

		Percentange in agreggate mixture						
		40,0%	10,0%	38,0%	12,0%		SUBAREA D (Δ)	
Sieve Designation ASTM E11	Sieve size (mm)	**0 - 5 mm**	**6 - 11 mm**	**12 - 25 mm**	**26 - 55 mm**	**Aggregate mixture**	Lower limit D (Δ)	Upper limit D (Δ)
1 1/2"	38,1	100,00	100,0	100,00	100,00	100,0	100	100
1"	25,0	100,00	100,0	99,42	46,40	93,3	95	100
3/4"	19,0	100,00	100,00	82,75	35,02	85,6		
1/2"	12,5	100,00	100,00	48,66	33,57	72,5	61	80
3/8"	9,50	100,00	98,92	26,07	33,18	63,8	51	73
No 4	4,75	99,44	40,05	11,43	32,10	52,0	33	56
No 8	2,36	74,16	16,20	10,32	31,78	39,0	21	43
No 16	1,18	52,90	15,30	9,68	31,54	30,2	12	32
No 30	0,60	37,84	14,62	9,01	31,26	23,8	6	23
No 50	0,30	24,83	13,77	8,07	30,83	18,1	3	14
No 60	0,25	22,59	13,55	7,84	30,71	17,1	2	13
No 200	0,075	14,08	11,54	6,34	30,03	12,8		

Table 4 Theoretical aggregates' mixture grading.

3.2 Particle shape of coarse aggregates

The shape of aggregates is required only for coarse aggregates that pass the 4 mm sieve and are retained on the 80 mm sieve. It is determined in terms of the flakiness index according to EN 933-3. This test consists of two sieving operations and the flakiness index is calculated as the total mass of particles passing the bar sieves expressed as a percentage of the total dry mass of particles tested. The results were related to the requirements of Standard EN 12620 [7]. EN 12620 does not provide an upper or a lower limit but instead specifies categories according to the value of flakiness index. The results are presented in Table 5.

Frame	**Flakiness Index**	**Category Category (according to EN12620)**
6mm-11mm	FI = 12 < 15	FI_{15}
12mm-25mm	FI = 10 < 15	FI_{15}
26mm-55mm	FI = 28 < 35	FI_{35}

Table 5 Flakiness index.

3.3 Shell content of coarse aggregates

This property is applied to aggregates with particle size fractions d_i/D_i where $D_i \leq 63$ mm and $d_i > 4$ mm (coarse aggregates) and is determined according to EN 933-7. The test consists of sorting by hand, shells and shell fragments from a test portion of coarse aggregate. The shell content is determined as the proportion of the mass of shells and shell fragments to the mass of the test portion. The shell content, SC, is expressed as a percentage. In our sample, there were neither shells nor shell fragments, so shell content equals: SC = 0%. Standard EN 12620 specifies categories based on the SC values just as those of flakiness index [7]. Our sample resided in category SC_{10} (SC = 0% < 10).

3.4 Fines quality

The harmfulness of fines in fine aggregate, including filer aggregate, was evaluated using two different indicators: (i) Sand equivalent and (ii) Methylene blue test according to standard tests ASTM D 2419 and EN 933-9 accordingly.

3.4.1 Sand equivalent (SE)

The purpose of this test method is to indicate, under standard conditions, the relative proportions of clay-like or plastic fines and dust in granular soils and fine aggregates that pass the No. 4 (4.75-mm) sieve. The term "sand equivalent" expresses the concept that most granular soils and fine aggregates are mixtures of desirable coarse particles, sand, and generally undesirable clay or plastic fines and dust. The SE value was estimated to 59. According to Greek standard ELOT 401 the SE value should exceed the lower limit of SE=65. Therefore, fine RA are not appropriate for use as concrete aggregates.

3.4.2. Methylene blue test (MB)

During this test, increments of a solution of methylene blue are added successively to a suspension of the test portion in water. The absorption of dye solution by the test portion is checked after each addition of solution and is related to the fines quality. In particular, the higher the MB value, the lower the fines quality. The MB value was estimated to 2. In standard EN 12620, is mentioned that MB value should be less than a particular specified limit, but this limit is not specified. According to the French Standard NF XP P 18-540 this value should be lower than 1 (MB<1) [8]. In addition, research projects compiled in Greece define that the value of MB should be lower than 1.2 (MB<1.2) [9] Therefore, this test also concludes to the unsuitability of fine RA for use as concrete aggregates.

3.5 Resistance to fragmentation of coarse aggregates

This property refers to the measure of degradation of mineral aggregates of standard grading resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres, the number depending upon the grading of the test sample. It was carried out according to ASTM C131 test method that is applied to coarse aggregate smaller than 37.5 mm (11⁄2 in.) using the Los Angeles testing machine (LA). The LA value was estimated to 42.90% higher than 40% that is the lower limit specified by ELOT 401. As a consequence, this value does not exclude the use of coarse RA as concrete aggregates.

3.6 Specific Gravity and Absorption

Test method ASTM C 127 is used to determinate the specific gravity and absorption of coarse aggregate. The specific gravity is expressed as bulk specific gravity (SSD) (saturated-surface-dry) and both bulk specific gravity (SSD) and absorption are based on aggregate after 24 h soaking in water. Alike, test method ASTM C 128 is used to determine the bulk specific gravity (SSD) (saturated-surface-dry) and absorption of fine aggregate after 24 h soaking in water. The tests' results are presented in Table 6.

	Recycled aggregates			
	Fine	Coarse		
	0 - 5 mm	6 - 11 mm	12 - 25 mm	26 - 55 mm
Absorption (%)	8,90	4,80	5,40	6,80
Bulk specific gravity/ saturated- surface -dry (kg/m^3)	2,25	2,36	2,39	2,34

Table 6 Bulk specific gravity (SSD) and absorption of RA.

Both Standards ELOT 401 and EN 12620 do not specify lower or higher limits as a requirement. Owning to this, in order to criticize the results a comparison to the bulk specific gravity (SSD) and absorption of NA was made. The corresponding values are presented in Table 7. We observe that both RA and NA have similar bulk specific gravity (SSD) but on the other hand the absorption of the RA values is three to four times higher than those of the NA. This high value of the absorption may cause serious problems during the production of concrete.

	Natural aggregates		
	Fine	Coarse	
	0 -5 mm	6 - 9,5 mm	10- 25 mm
Absorption (%)	2,60	1,35	1,40
Bulk specific gravity/ saturated- surface -dry (kg/m^3)	2,52	2,56	2,60

Table 7 Bulk specific gravity (SSD) and absorption of NA.

3.7 Durability – Soundness of Aggregate by Use of Sodium Sulfate

The durability is tested by estimating the aggregates' soundness when subjected to weathering action in concrete or other applications. This is accomplished by repeated immersion in saturated solutions of sodium sulfate followed by oven drying to partially or completely dehydrate the salt precipitated in permeable pore spaces, according to AASHTO T 104 Standard. The results compared to the higher specified limits by ELOT 401, are presented in table 8. It is obvious that fine RA do not fulfill the requirements in order to be used as concrete aggregates as opposed to coarse RA.

Mass Loss	*Estimated value %*	*Higher specified limits by ELOT - 401*
Fine aggregate	*19%*	*10%*
Coarse aggregate	*9%*	*12%*

Table 8 Durability.

4. Conclusions

The tests' results, led us to the conclusion that the use of fine recycled aggregate in concrete for structural use is generally not recommended. Fine recycled aggregates (with nominal particle size: 0-5mm) should not be used in concrete production due to their low quality: both sand equivalent value and blue methylene test value are lower than those required by the corresponding standards. The same problem is presented in fine RA's durability.

Contrary, the tests did not exclude the use of coarse recycled aggregate. However, only those with those with nominal particle size: up to 25mm, should be used in concrete production as their grading resembles to the one of natural aggregates. However, their high water absorption and their heterogeneity may affect in a negative way the concrete's properties. Further experimental investigation is required in order to reassure that their use in concrete production is possible. Probably, RA could be used in lower end applications of concrete. Either way the use of recycled aggregates in concrete provides a promising solution to the problem of C&D waste management. Greater efforts are needed in the direction of creating awareness, and relevant specifications to clearly demarcate areas where RA can be safely used.

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