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A Proposal for the Use of Recycled Aggregates in Concrete in Greece †

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Abstract: Regulations for building materials in Greece do not allow for the use of recycled aggregates in concrete. The HERACLES Group, aiming to motivate the adoption of provisions in the national regulation, launched a project to evaluate the safe use of recycled aggregates in ready-mix concrete units. In this report, updated results are presented comparing the technical properties of concrete mixes containing only crushed limestone aggregates (reference mixes) and mixes containing partially replaced crushed limestone aggregates with recycled aggregates (control mixes). The current results indicate equivalence between the reference and control compositions in terms of both physicomechanical and durability properties. These experimental results and the practices of other European countries indicate that in Greece, based on EN 12620 and EN 206 standards, it is at least safe to use recycled coarse aggregates (≥4 mm) of classes Rc90 and Rcu95 with production and quality certification and a substitution rate up to 20% of crushed limestone aggregates. In addition, the application concerns non-prestressed concrete with a strength class up to C30/37 and an exposure class up to XS1.

Keywords: recycled aggregates; concrete

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1. Introduction

Excavation, Construction and Demolition Waste (CDW) is one of the most "productive" waste sectors in the European Union (EU), producing approximately 850 million tons annually, an amount that represents 25–30% of all EU waste. These are produced during new construction, the total or partial demolition of buildings and in general infrastructure and road construction projects. As such, they consist of a multitude of materials (concrete, bricks, plaster, wood, glass, metals, asphalt, plastics, soil), many of which can be recycled.

Recycling has been characterized as a priority by the EU and has been reflected in Directive 2008/98/EC of the European Parliament. According to the same directive, which has been incorporated into Greek Legislation since 2010, all member states must achieve a recycling rate of at least 70% of CDW by 2020.

In order to reduce the environmental footprint in concrete production, the use of recycled aggregates from CDW is foreseen in the EU countries based on the following standards:

EN 206:2021: "Concrete–Specification, performance, production and conformity" [1].
EN 12620:2002+A1 (2008): "Aggregates for concrete" [2].

Table 1 (Table E.2 in EN 206: 2021) shows the recommended percentage of replacement of natural aggregates by recycled coarse aggregates ≥ 4 mm in concrete depending on its exposure class (e.g., X0, XC1, XC2, etc.) and the quality of the coarse recycled aggregates

used (e.g., Type A, Type B). In Table 2, the symbols for the constituents of the recycled aggregate type are presented.

Table 1. Maximum permissible percentage (% by mass) replacement of coarse aggregates in concrete mixes specified in EN 206.

Recycled Aggregate Type	Exposure Classes			
	X0	**XC1, XC2**	**XC3, XC4, XF1, XA1, XD1**	**All Other Exposure Classes [a]**
Type A:(Rc_{90}, Rcu_{95}, $Rb_{10\text{-}}$, $Ra_{1\text{-}}$, $FL_{2\text{-}}$, $XRg_{1\text{-}}$)	50%	30%	30%	0%
Type B [b]: (Rc_{50}, Rcu_{70}, $Rb_{30\text{-}}$, $Ra_{5\text{-}}$, $FL_{2\text{-}}$, $XRg_{2\text{-}}$)	50%	20%	0%	0%

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%. [b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

Table 2. The symbols for the constituents of the recycled aggregate type.

Rc	**Concrete, Concrete Products, Mortar, Concrete Masonry Units**
Ru	Unbound aggregate, natural stone, hydraulically bound aggregate
Rb	Clay masonry units (i.e., bricks and tiles), calcium silicate masonry units, aerated non-floating concrete
Ra	Bituminous materials
Rg	Glass
	Other: cohesive (i.e., clay and soil)
X	Miscellaneous: metals (ferrous and non-ferrous), non-floating wood, plastic and rubber, gypsum plaster
90	Index for content at least 90%
2-	Index for content less than or equal 2%

The EU countries follow the European standards as a basis to formulate national legislated practice for the use of recycled aggregates in concrete. Structured information on the European and Greek regulatory framework for the use of recycled aggregates from CDW in concrete and current European practices was presented in a corporate workshop of the Holcim Group [3]. The Austrian practice is of particular interest regarding the controlled production and use of recycled aggregates from CDW in concrete [4]. In more detail:

- Coarse recycled aggregates (≥4 mm) are used at a rate of 20–100%, based on exposure and compressive strength classes. In most cases, coarse recycled aggregates of the high-quality class ≥Rc_{90}, or ≥$Rcu_{90,}$ are used.
- The possibility of using recycled sand remains limited. Recycled sand usually includes impurities not compatible for the manufacture of concrete, except in the case where the recycled material is derived solely from concrete demolition. The cost of removing impurities leads to the use of recycled sand in other applications.
- Aggregate requirements are based on the EN 12620 standard, with additional ones depending on their nature, for example, alkali–silica reaction testing in Germany, or the use of recycled aggregates of complex granulometry [=all-in aggregates] in Austria.
- Various qualities (high and low, Type A, Type B, etc.) of recycled aggregates are distinguished, all of which are used in the production of concrete of different exposure classes, strength classes and percentages depending on their characteristics.

In Table 3, depending on the country, the particle size limits between fine and coarse aggregates are distinguished. In France, Austria and the Netherlands, the use of recycled sand is also allowed.

Table 3. Particle size discrimination and recycled aggregate use in European countries.

Country	Fine Aggregates	Coarse Aggregates
Germany	No use mentioned	Defined as ≥2 mm
France	Use of recycled sand	
Austria	Use is allowed. Defined as ≤8 mm	
Poland	No use mentioned	Defined as ≥4 mm
United Kingdom	Not recommended	Defined as ≥4 mm
Belgium	Not recommended	
Netherlands	Recycled sand ≤ 4 mm may be used in substitution of up to 20% of non-recycled sand, without certification but not in combination with recycled coarse aggregates	
Italy	Not recommended	Defined as ≥4 mm
Spain	Not allowed	Defined as ≥4 mm

In Table 4, the requirements for the use of coarse recycled aggregates of high quality (Type 1, Type A, $\geq Rc_{90}$, or $\geq Rcu_{90}$) are presented for each country for exposure classes X0, XC1, XC2, XC3, XC4, XS1 and XS2, which are the most common in Greece. The XS3 exposure class, according to Greek concrete regulation, refers purely to port infrastructure, and XS1 and XS2 to coastal environments. It can be seen that coarse recycled aggregates can be used in strength classes up to C50/60 and in all exposure classes at various percentages. The Netherlands allow the use of certified recycled aggregates up to 100% with modifications in the structural calculations. Strict requirements of exposure classes XS1 and XS2 concern countries with extensive exposure to coastal environments, such as Greece; it appears that the minimum substitution with coarse recycled aggregates is 20%, except for the exposure class XS2 in France, for which the minimum is 10%.

Table 4. Recycled coarse aggregate maximum percentage of participation for different exposure classes and for maximum compressive strength class.

Country	Maximum Participation % for Each Exposure Class							Maximum Strength Class
	X0	XC1	XC2	XC3	XC4	XS1	XS2	
Germany	45	45	45	45	45			
France	60	40	40	30	30	30	10	
Austria	50	50	50	50	50			
Poland	50	30	30	30	30			
United Kingdom	100	100	100	100	100			C16/20
	20	20	20	20	20	20	20	C40/50
	100	100	100	100	100			
Belgium	50	30	30	20	20			C30/37
Netherlands (a)	30	30	30	30	30	30	30	C50/60
(b)	50	50	50	50	50	50	50	
(c)	100	100	100	100	100	100	100	
Italy	30	30	30	30				C30/37
	20	20	20	20	20	20	20	C45/55
Spain	20	20	20	0	20	20	20	C40/50

(a) Without certification, (b) With certification—without modifications in the structural design, (c) With certification—with modifications in the structural design.

As in Greece the National Concrete Regulation does not permit the use of recycled aggregates from CDW in concrete, the HERACLES Group runs a project aiming to motivate the adoption of related provisions in the national regulation for their use. The project creates updated results from physicomechanical and durability tests to validate the safe use of recycled aggregates in ready-mixed concrete units. In this paper, results on the properties of reference mixes with crushed limestone aggregates and mixes with recycled

aggregates are compared. Laboratory mixes were prepared at EKET (Concrete R&D Central Laboratory, HERACLES Group), and industrial mixes were prepared at the Lafarge Beton (HERACLES Group) plant in Rafina. Raw material characterization was carried out by EKET, the determination of the chemical properties (water-soluble sulfates and acid-soluble chlorides) was carried out by HERACLES Environmental Laboratory and durability tests was carried out by NTUA's Reinforced Concrete Laboratory.

2. Raw Material Characterization

2.1. Cement

Cement CEM II/B-M (P-W-L) 32.5 N of HERACLES GCC was used, the strengths of which are shown in Table 5.

Table 5. Compressive strength of Cement CEM II/B-M (P-W-L) 32.5 N (EN 196-1) [5].

Lab Code	Compressive Strength (MPa)		
	2 d	7 d	28 d
49863	22.8	34.5	44.3

2.2. Crushed Aggregates

Table 6 and Figure 1 show the properties of the crushed aggregates produced at Lafarge Beton Quarry in Mesaio, Thessaloniki, and used in the laboratory mixes.

Table 6. Properties according to standards of the used limestone crushed aggregates grades in the mixes.

Property	*Grade/Lab Code*		
	Gravel/49377	Fine Gravel/48436	Crushed Sand/49378
Flakiness index, % (EN 933-3)	4.7	8.8	-
Sand equivalent, % (EN 933-8)	-	-	77
Methylene Blue value, g/kg (EN 933-9)	-	-	0.25
Los Angeles, % (EN 1097-2)	-	26.0	-
Apparent particle density ρ_a, kg/L (EN 1097-6)	2.69	2.68	2.60
Oven-dried particle density, ρ_{rd}, kg/L (EN 1097-6)	2.66	2.65	2.57
Water absorption, % (EN 1097-6)	0.32	0.40	1.55

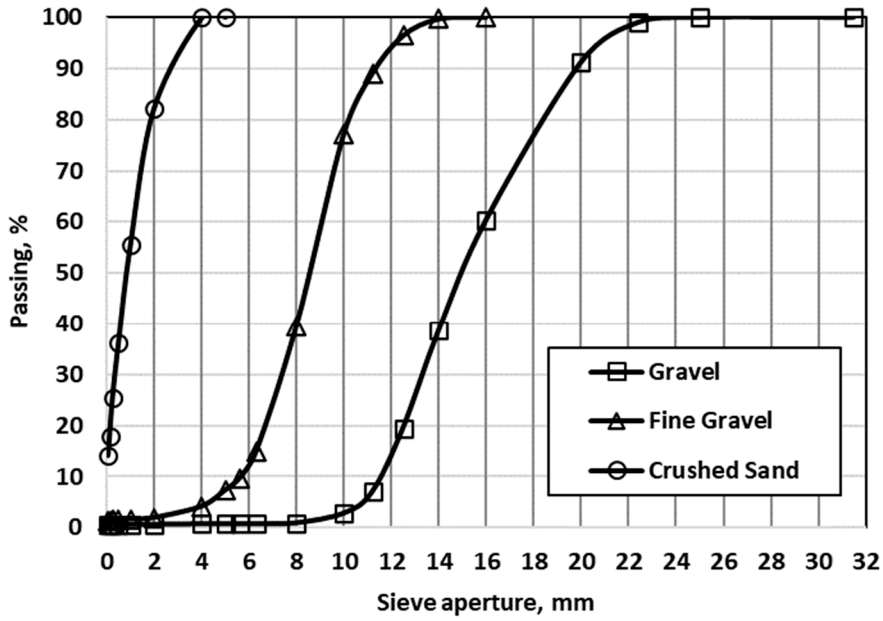


Figure 1. Sieve analysis of limestone crushed aggregates.

2.3. Recycled Aggregates

The recycled aggregates were provided by PSALLIDAS SA recycling unit, produced from a mixture of excavation and demolition materials. Their properties are shown in Table 7 and Figure 2.

Table 7. Properties of recycled aggregates used in (a) lab concrete mixtures and (b) industrial concrte mix.

Property	*Grade/Lab Code*		
	Gravel [(a)] /49859	**Fine Gravel [(a),(b)] /49860**	**Gravel [(b)] /49957**
Flakiness index, % (EN 933-3)	-	8.5	-
Los Angeles, % (EN 1097-2)	-	28.4	-
Classification (EN 933-11)	Rcu_{95}	Rcu_{95}	Rcu_{95}
Apparent particle density ρ_a, kg/L (EN 1097-6)	2.71	2.72	2.70
Oven-dried particle density, ρ_{rd}, kg/L (EN 1097-6)	2.65	2.64	2.64
Water absorption, % (EN 1097-6)	0.77	1.04	0.90

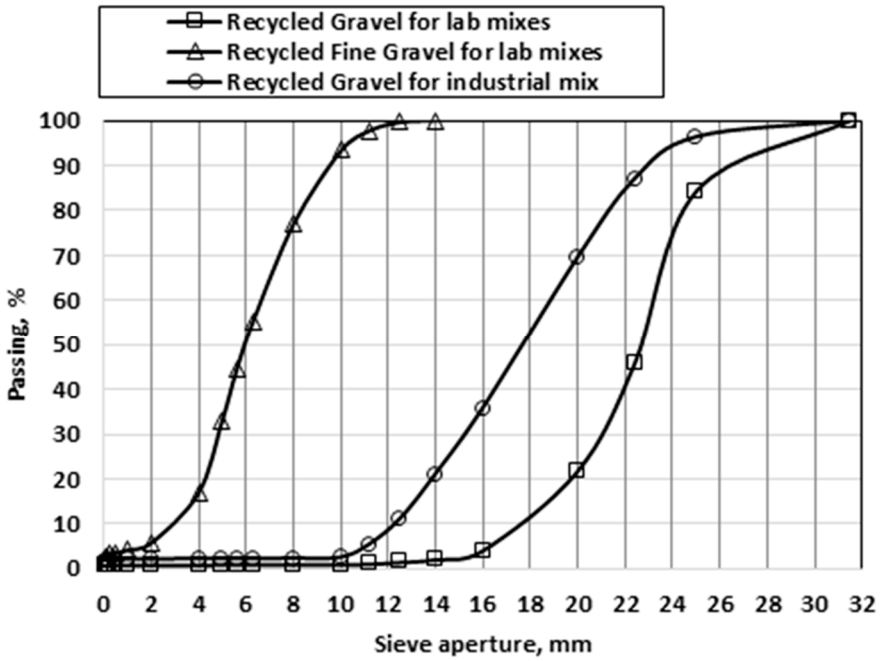


Figure 2. Sieve analysis of recycled aggregates for lab and industrial mixes.

Tables 6 and 7 show that the value of crushing resistance (Los Angeles) of the recycled aggregates is significantly lower than the allowed upper limit of 40%. The water absorption value of the recycled aggregates appears to be clearly greater than that of the limestone coarse crushed aggregates.

Table 8 shows the properties of the recycled aggregates within the limits of EN 206 (Table E.3) [1]. The stability of the properties, through observation over a one-year period, is indicated from the value range. The recycled aggregates fully comply with the requirements of EN 12620.

Table 8. Recycled aggregate properties.

Property	§ EN 12620	Type	Category EN 12620	Gravel	Fine Gravel
Fines content	4.4	A+B	Value to be declared	0.7–0.8	2.5–2.6
Flakiness index	4.6	A+B	$\leq FI_{50}$	4.3	8.5
Los Angeles	5.2	A+B	$\leq LI_{50}$	-	28.4
Oven-dry density, ρ_{rd}	5.4.1	A	≥ 2.1 Mg/m^3	2.64–2.65	2.57–2.64
		B	≥ 1.7 Mg/m^3	-	-
Water absorption	5.4.2	A+B	Value to be declared	0.77–0.95	1.04–1.43
Constituents	6.3	A	Rc_{90}, Rcu_{95}, Rb_{10-}, Ra_{1-}, FL_{2-}, XRg_{1-}	Rcu_{95} = 99%, Rb_{10-} = 0%, Ra_{1-} = 0%, FL_{2-} = 0%, XRg_{1-} = 0%	
		B	Rc_{50}, Rcu_{70}, Rb_{30-}, Ra_{5-}, FL_{2-}, XRg_{2-}	-	-
Water-soluble sulfate content	6.4.3	A+B	$\leq SS_{0\cdot2}$	$SS_{0,2}$	
Acid-soluble chloride content	6.5	A+B		0.014%	
Influence on the initial setting time	6.7.1	A+B	$\leq A_{40}$	A_{10}	

3. ECOPact Lab Mix Design Results

ECOPact is a mark of "green" concrete mixes of the HERACLES Group, with a lower CO_2 footprint. The project aims to compare the properties of ECOPact mix designs with crushed limestone aggregates and their partial replacement with recycled aggregates. The mixes apply to the most commercial strength classes C16/20, C20/25, C25/30 (XS1/XS2) and C30/37.

3.1. Mix Design–Fresh and Hardened Concrete Properties

Tables 9 and 10 present the mix designs and physicomechanical properties. In all mixes, the percentage of replacement of coarse aggregates with recycled ones is 30%. The results indicate that there are no differences for strength classes C16/20, C25/30 and C30/37 between the properties of the reference mix and the control mix within the limits of laboratory repeatability. For the strength class C20/25, the hardened concrete properties of the ref. mix seem to be 10% higher than those of the control mix.

Table 9. Ingredients and properties of ECOPact laboratory mix designs of strength classes C16/20 and C20/25, with and without recycled aggregates.

	C16/20 ECOPact		C20/25 ECOPact	
Lab code	Ref mix 9479, 9546	Control mix 9481, 9547	Ref mix 9483, 9516	Control mix 9484, 9518
Cement CEM II 32,5N, kg/m^3	265	265	280	280
Water, kg/m^3	184	184	185	185
Gravel, kg/m^3	660	464	666	466
Fine gravel, kg/m^3	126	88	154	108
Sand, kg/m^3	1127	1129	1077	1077
Recycled gravel, kg/m^3		199		201
Recycled fine gravel, kg/m^3		40		47
Admixture, kg/m^3	1.06	1.06	1.68	1.68
Slump 5 min, cm	14	15	10	15
Slump 30 min, cm	9	10	7	10
Cs 3d, MPa	18.9	19.7	22.0	20.8
Cs 7d, MPa	24.8	25.1	28.5	25.8
Cs 28d, MPa	27.6	29.5	32.4	31.4
Cs 90d, MPa	29.5	29.6	37.0	33.9
Modulus of elasticity at 28d, GPa	34.2	32.4	34.0	29.3

Table 10. Ingredients and properties of ECOPact laboratory mix designs of strength classes C25/30 and C30/37, with and without recycled aggregates.

	C25/30 ECOPact		C30/37 ECOPact	
Lab code	Ref mix 9497, 9528	Control mix 9498, 9529	Ref mix 9492, 9524	Control mix 9493, 9526
Cement CEM II 32,5N, kg/m^3	330	330	320	320
Water, kg/m^3	180	180	170	170
Gravel, kg/m^3	642	450	680	477
Fine gravel, kg/m^3	212	148	168	118
Sand, kg/m^3	1009	1009	1053	1054
Recycled gravel, kg/m^3		193		205
Recycled fine gravel, kg/m^3		65		51
Admixture, kg/m^3	2.15	2.15	2.24	2.24
Slump 5 min, cm	14	14	23	22
Slump 30 min, cm	8	7	23	18
Cs 3d, MPa	27.4	27.6	32.2	31.7
Cs 7d, MPa	33.7	32.7	38.6	38.3
Cs 28d, MPa	39.5	40.5	48.6	46.1
Cs 90d, MPa	44.9	46.9	54.5	50.9
Modulus of elasticity at 28 d, GPa	38.6	37.1	38.9	36.6

3.2. Durability Results

ECOPact laboratory specimens were subjected to durability tests, as described in Table 11.

Table 11. Durability tests for ECOPact mix designs.

Test	Standard	Comments
Chloride migration coefficient	EN 12390-18 [6]	Cylindrical specimens: d 100 × h 200 mm Curing: 28 and 90 days Number of samples: 2/test
Accelerate carbonation	EN 12390-12 [7]	Cylindrical specimens: d 100 × h 200 mm Curing: 28 and 90 days Conditioning: 14 days Exposure: 28 and 70 days Number of samples: 2/test

The specimens for the determination of the chloride migration coefficient were divided into two groups, one with an age of 28 days and the other one with an age of 90 days of curing in a climate chamber (20 ± 2 °C, RH ≥ 95%).

For carbonation testing, the specimens were divided into two groups, one cured for 28 days and the other for 90 days in a curing chamber at (20 ± 2 °C, RH ≥ 95%). After curing, the test specimens were conditioned in a laboratory air environment for 14 days and then placed in a storage chamber with a carbon dioxide concentration at a percent of 3.00 ± 0.10% v/v, a temperature of 20 ± 2 °C and an RH of 57 ± 3%. Carbonation depth was measured after 28 and 70 days of exposure.

Tables 12–14 present the results. Durability measurements indicate that there are no significant differences between the reference mix designs of strength classes C16/20 up to C30/37 and the corresponding control mixes using recycled aggregates.

Table 12. Chloride migration coefficient (D_{nssm}), standard deviation (Sr) and coefficient of variation (CoV) according to EN 12390-18, of concrete samples at the age of 28 and 90 d.

A/A	Lab Mix Design	28 Days			90 Days		
		$D_{nssm} \cdot 10^{-12}$ (m^2/s)	Sr	CoV%	$D_{nssm} \cdot 10^{-12}$ (m^2/s)	Sr	CoV%
1	9479-ref	29.0	2.4	8.4	19.9	1.6	7.9
2	9481-cont.	29.9	1.6	5.4	23.3	2.7	11.6
3	9516-ref	30.1	2.3	7.5	20.6	1.4	6.6
4	9518-cont.	29.8	3.3	11.0	20.1	1.3	6.7
5	9524-ref	26.0	1.3	4.9	13.5	0.6	4.3
6	9526-cont.	23.2	1.7	7.5	12.3	1.3	10.6
7	9528-ref	18.7	0.6	3.3	13.6	1.2	8.6
8	9529-cont.	19.5	1.1	5.6	11.7	0.4	3.6

Table 13. Carbonation depth of samples cured in chamber for 28 d, after 28 and 70 days of exposure.

A/A	Lab Mix Design	28 Days			70 Days		
		CO_2 Depth (mm)	Sr	Cov%	CO_2 Depth (mm)	Sr	Cov%
1	9479-28 (ref)	8.4	0.4	5.2	14.9	0.3	2.2
2	9481-28 (cont.)	8.7	0.4	4.4	14.4	0.4	2.7
3	9516-28 (ref)	9.8	1.3	13.2	16.2	0.6	3.6
4	9518-28 (cont.)	7.5	1.7	22.7	13.5	0.9	7.0
5	9524-28 (ref)	5.8	0.2	3.6	9.5	0.1	1.2
6	9526-28 (cont.)	4.5	0.8	17.0	7.5	0.4	5.5
7	9528-28 (ref)	5.9	0.9	15.4	9.9	0.7	6.8
8	9529-28 (cont.)	4.9	1.3	26.6	9.0	1.4	15.0

Table 14. Carbonation depth of samples cured in chamber for 90 d, after 28 and 70 days of exposure.

A/A	Lab Mix Design	28 Days			70 Days		
		CO_2 Depth (mm)	Sr	Cov%	CO_2 Depth (mm)	Sr	Cov%
1	9479-90 (ref)	8.0	0.9	11.0	15.9	1.7	10.7
2	9481-90 (cont.)	7.2	1.4	19.6	17.9	1.4	7.6
3	9516-90 (ref)	12.3	0.0	0.00	17.2	2.1	12.0
4	9518-90 (cont.)	10.0	1.4	13.6	14.5	0.9	6.5
5	9524-90 (ref)	5.8	1.3	22.6	8.2	0.8	9.7
6	9526-90 (cont.)	3.6	1.4	38.0	5.0	3.1	60.8
7	9528-90 (ref)	2.1	0.6	28.8	6.0	0.5	8.4
8	9529-90 (cont.)	3.8	0.0	0.0	8.0	1.1	13.9

Based on the results at 28 days, all mix designs are comparatively characterized by low resistance to chloride penetration.

Based on the standard deviation (Sr) and coefficient of variation values (coefficient of variation, CoV, %), the criteria set by the EN 12390-18 standard (CoV < 11%) are met.

The increased curing of the samples appears to improve the mix designs' carbonation resistance.

4. C25/30 Industrial Mix Design Results

Table 15 presents the physicomechanical test results of the industrial concrete mix produced at the Lafarge Beton plant in Rafina. In these mixes, the percentage of replacement of coarse crushed gravel with recycled gravel is 30%.

Table 15. Ingredients and properties of industrial concrete mix of C25/30 strength class, with and without recycled aggregates.

	Ref Mix	Control Mix
Cement CEM II 32,5N, kg/m^3	310	310
Water, kg/m^3	174	176
Gravel, kg/m^3	625	438
Fine gravel, kg/m^3	160	160
Sand, kg/m^3	1115	1115
Recycled gravel, kg/m^3		188
Admixture, kg/m^3	2.17	2.17
Slump 5, cm	14	15
Slump 30, cm	9	11
Slump 60, cm	6	9
Cs 3d, MPa	26.9	27.8
Cs 7ημ, MPa	35.2	37.4
Cs 28d, MPa	41.1	43.2
Modulus of elasticity 28d, GPa	34.4	33.9
Water depth under pressure at 28 d, mm	15.2	15.1
Pore volume at 28 d, % v/v	11.9	11.8

The results of Table 15 indicate that there are no differences between the properties of the reference mix design and the industrial control mix.

5. Conclusions

The experimental results so far, the references [1–4,8–10] and the practices of European countries indicate the use of recycled aggregates (≥4 mm) as a safe action to be introduced in Greece under EN 12620 and EN 206 standards, with the following requirements:

- Classes Rc_{90} and $Rcu_{95;}$
- With production and quality certification;
- In concrete mix designs;
- Non-prestressed;
- In exposure classes up to XS1;
- In strength classes up to C30/37;
- With a substitution rate of recycled aggregates up to 30%.

It is observed that these conclusions are based on experimental studies, using recycled aggregate deliveries for the duration of one year from one supplier. Recycled aggregates' technical characteristics are quite stable, and their water absorption values are low enough.

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