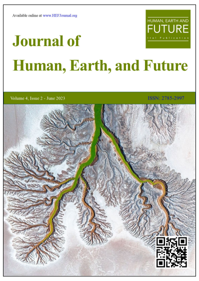
HUMAN, EARTH AND FUTURE
Ital Publication

ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 4, No. 2, June, 2023



Recycled Concrete Aggregates: A Promising and Sustainable Option for the Construction Industry

Driton Kryeziu [1], Feti Selmani [1*], Armend Mujaj [2], Igli Kondi [3]

[1] *Civil Engineering and Infrastructure Department, University for Business and Technology UBT, Pristina, Republic of Kosovo.*

[2] *Civil Engineering Faculty, University of Prishtina, Pristina, Republic of Kosovo.*

[3] *Civil Engineering Faculty, Trana Polytechnic Faculty, Tirana, Albania.*

Received 24 February 2023; Revised 11 May 2023; Accepted 19 May 2023; Published 01 June 2023

Abstract

The recycling of locally collected concrete waste is being promoted toward reducing the carbon footprint. In the preparation of concrete, recycled concrete aggregates (RCA) are encouraged instead of natural aggregates (NA), as they can help reduce the consumption of virgin materials, the extraction and transportation of which can be costly and environmentally damaging. In this context, we conducted an experimental study on various concrete mixes to evaluate the effect of using RCA instead of NA on the physical and mechanical properties of fresh and hardened concrete. The main novelty of our study lies in meeting one of the principles of circular economy, i.e., reducing the carbon footprint, by recycling concrete waste collected locally. We prepared and investigated test specimens containing 0%, 20%, 40%, and 60% of fine and coarse recycled concrete aggregates. Results for fresh concrete were determined for temperature, consistency, air content, and density, while on the other side, in hardened concrete, results were determined for compressive strength, tensile splitting strength, and density. All results were determined experimentally and then compared. Our results showed that, with the use of RCA in the concrete mix, construction companies can significantly reduce their carbon footprints and help conserve natural resources. RCA can help create a more sustainable and affordable construction industry and is better suited to meet future challenges. Our study can serve as a basis for advancing the application of RCA in the preparation of concrete for sustainable construction.

Keywords: Concrete; Recycled Concrete Aggregates; Natural Aggregates; Admixtures; Mix Design; EN 206.

1. Introduction

Concrete is the second-most commonly used material in the world after water. Its usage fuels the growth of the construction industry. However, the cement industry is energy-intensive [1, 2], and cement production generates substantial amounts of carbon dioxide emissions. The cement industry currently represents approximately 7% [3] of global CO_2 emissions. According to Eurostat, in 2020 alone, the construction sector was responsible for 37.5% of all waste generated by economic activities in the European Union (EU27). This corresponds to 1,733 kg of waste per capita within the EU27, an increase of 12.5% since 2004.

* Corresponding author: feti.selmani@ubt-uni.net

http://dx.doi.org/10. 28991/HEF-2023-04-02-03

Kosovo, a potential EU candidate, produces 1,414 kg of waste per capita, an increase of approximately 7.3% since 2010, and in this share, 4.4% of the waste is classified as hazardous [2]. Global CO_2 emissions from energy generation and industrial processes rebounded in 2021 to reach their highest ever annual levels, an increase of up to 6% from 2020 [4]. To mitigate the impact of climate change resulting from such emissions, the EU has put forward the European Green Deal (EGD), a set of policy initiatives to transform the EU into a modern, resource-efficient, and competitive economy [5], with objectives such as a 55% reduction in emissions by 2030 and net-zero emissions by 2050. However, the UNEP 2022 Global Status Report has shown that the building sector will remain off-track in its contribution toward decarbonization by 2050. This has placed significant pressure on the economy in order to comply with the policy of net-zero emissions. Nevertheless, there is an opportunity to realize the need to react urgently to meet this objective. According to the International Energy Agency (IEA), global cement production in 2006 was 2.55 billion tons, whereas in 2021 [6], it increased to 4.4 billion tons, an increase of 72.5%.

All three pillars of sustainability, namely the environment, society, and economy, must be considered, and the best approach to decreasing carbon emissions is to apply the principle of circular economy. The novelty of this study lies in the application of one of the principles of CEP: reducing the carbon footprint through the recycling of locally collected concrete waste.

This paper presents the results of an experimental study conducted on the effects of replacing natural fine and coarse aggregates (NCA) with recycled fine and coarse aggregates (RCA) on the properties of fresh and hardened concrete. The adoption of RCA promises not only environmental benefits but also economic advantages. As the global community intensifies its commitment to sustainability, the construction industry must adapt and innovate. RCA represents a promising avenue to achieve the dual objectives of reduced environmental impact and enhanced economic viability. This paper endeavors to shed light on the transformative potential of RCA, providing insights for policymakers, engineers, and stakeholders alike. Through rigorous analysis and case studies, it seeks to underscore the role of RCA as a cornerstone in the foundation of a more sustainable and resilient construction industry. As we navigate this terrain, it becomes apparent that RCA is more than just a construction material; it is a stepping stone toward a greener and more economically efficient future for the construction industry.

2. Materials and Methods

2.1. Materials

Cement

The cement used in this study was Portland limestone cement (CEM II/A-LL 42.5 R), supplied by COLACEM and commercially available in Kosovo. The specific density of the cement was 3.02 g/cm^3. Table 1 presents its chemical properties. Table 2 presents its mechanical and physical properties.

Table 1. Chemical composition of Portland limestone cement (%) (supplied by COLACEM, CEM II/A-LL 42.5 R)

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Specific mass (g/cm^3)	Specific surface area (cm^2/g)
67.09[1]	21.32[1]	4.80[1]	3.06[1]	2.26[1]	0.90[1]	-	-	3.02[1]	4200[1]
62.66[2]	17.62[2]	4.40[2]	2.74[2]	1.27[2]	2.77[2]	0.82[2]	0.25[2]	2.97[2]	-

[1] Data declared by the producer; [2] Data provided by the authors of the paper.

Table 2. Mechanical and physical results and requirements of the cement in accordance with EN 197-1 [7]

Strength class	Compressive strength (MPa)		Initial setting time (min)	Soundness (Expansion)
42.5 R	Early strength	Standard strength	-	-
	2 days	28 days	-	-
	25[1]	47[1]	180[1]	0[1]
	24.6[2]	48.5[2]	175[2]	1[2]
	≥20[2]	≥42.5[2]; ≤62.5[2]	≥60[2]	≤10[2]

[1] Data declared by the producer; [2] Data provided by the authors of the paper.

Mixing Water

Water is an important ingredient in concrete, as it actively participates in the chemical reactions with the cement. Because water helps achieve the strength of the cement gel, its quantity and quality must be carefully investigated [8–10]. The primary role of water in the concrete mixture is threefold: first, it interacts with the cement powder, producing hydration products; second, it serves as a lubricant that aids in the handling of fresh concrete mixtures; and third, it ensures the necessary space in the paste for the development of hydration products. Drinking water remains the best method for mixing concrete. For all the concrete mixtures, drinking water was used to produce concrete in accordance with EN 1008 [9]. Drinking water can be used in concrete mixes without testing or qualification [10]. There is a rule of thumb to determine whether water is suitable for mixing with concrete: If the water is considered potable, i.e., safe and suitable for human consumption, except for certain types of mineral water and water containing sugar, it is also considered appropriate for use in concrete production. The amount of water present in concrete and the water-to-cement ratio are perhaps the most essential elements for ensuring high-quality concrete production. However, an excessive amount of water can compromise the strength of concrete, whereas too little water can render concrete unmanageable. Consequently, to achieve a balance between the strength and workability of cement, the cement-to-water ratio and, consequently, the total amount of water should be appropriately selected during concrete manufacturing.

Admixtures

CEMENTOL® HIPERPLAST 235 LT (produced by TKK d.o.o. Srepenica of Slovenia) was used in all the concrete mixes. It is a new-generation, highly effective, special superplasticizer, particularly suitable for the preparation of ready-mixed concrete of higher consistency classes, which must have a longer workability time, or in the preparation of concrete used for higher-temperature applications. Dosages in the range of 0.4%–0.7% of the weight of cement are suitable for the most commonly used types of concrete (pumpable concrete of consistency class S4). Cementol Hiperplast 235 LT is particularly effective when a finer composition of the aggregate is used for the preparation of the concrete mix. The Cementol Hiperplast 235 LT plasticizer meets the requirements of the EN 934-1 [11] and EN 934-2 [12] standards (see Table 3).

Table 3. Chemical composition of Cementol Hiperplast 235 LT

Property	Values as declared
Appearance	Yellowish brown liquid
Density, 20°	(1.06 ± 0.02) kg/dm^3
pH	6.0 ± 1.0
Water-soluble chloride content	(Cl-) Chloride free
Alkali content (equivalent Na_2O)	$<3.0\%$

Natural Aggregates

Aggregates are important constituents of concrete. They constitute the body of the concrete, reduce shrinkage, and affect the overall cost of concrete. In this study, broken fine aggregate (0/4; Gf85) and coarse aggregates (4/8 and 8/16) (manufacturer: Vëllezërit e Bashkuar, Prizren, Kosovo) categorized as Gc85/20 by EN 12620 [13] were used. Tables 4 and 5 present analyses of some of the physical and mechanical properties of the aggregates.

Table 4. Particle density and water absorption

Fraction *d*/*D* (mm)	Apparent particle density (mg/m^3)	Particle density on an oven-dried basis (mg/m^3)	Saturated and surface-dried basis (mg/m^3)	Water absorption (%) WA_{24}
NA: 0/4	2.72	2.66	2.68	0.80
NA: 4/8	2.72	2.68	2.70	0.50
NA: 8/16	2.72	2.70	2.71	0.30
RCA: 0/4	2.61	2.53	2.59	3.45
RCA: 4/8	2.61	2.52	2.60	1.95
RCA: 8/16	2.61	2.64	2.60	1.82

Table 5. Loss Angeles (L. A) abrasion loss values (% of mass loss) of RCA and NA reported by different researchers [14]

References	L. A. abrasion mass loss (%)	
	RCA	NA
Snyder et al. (1994) [15]	20-45	15-30
Verian (2012), and Verian et al. (2013) [16, 17]	34-36	29-31
Li (2009) [18]	27.3	11.5
Wen et al. (2014) [19]	20-29	15
Yehia & Abdelfatah (2016) [20]	21-35	19-25
Hansen & Narud (1983) [21]	22-41	20-30
Ravindrarajah & Tam (1985) [22]	37-41	18
Ait Mohamed Amer et al. (2016) [23]	51.5	38.9
Kurda et al. (2017) [24]	43	28
Liu et al. (2011) [25]	42	31
Kryeziu et al. (2018) [26]	28.8	26

Recycled Aggregates

Several types of materials can be recycled and used as substitutes for natural aggregates (NA) during construction [14]. Recycled aggregates are obtained from the processing of inorganic materials previously used in construction. The British Standard specifies requirements for coarse RA only, excluding the use of fine RA in concrete production. Annex E, BS EN 206, recommends the use of coarse recycled aggregates with $d \geq 4$ mm. [27]. Recycled aggregates are derived by crushing inert construction and demolition (C&D) waste. It may be classified as a recycled concrete aggregate (RCA) when it comprises primarily of crushed concrete, or more generally as a recycled aggregate (RA) when it contains substantial quantities of materials other than crushed concrete.

Currently, only the use of coarse aggregates originating from construction or demolition waste is recommended for new concrete construction. In this study, RCA was used as the recycled aggregate (Figure 1). The use of RCA instead of NA has a positive impact on the environment and economy [14, 28]. After this analysis, the physical and mechanical properties of the recycled aggregate were determined in accordance with EN 12620 [13]. Figure 2 shows the granulometric curves of the natural fine and coarse aggregates, and of the recycled fine and coarse aggregates.

Figure 1. Process of crushing and fractionation of existing concrete to produce RCA

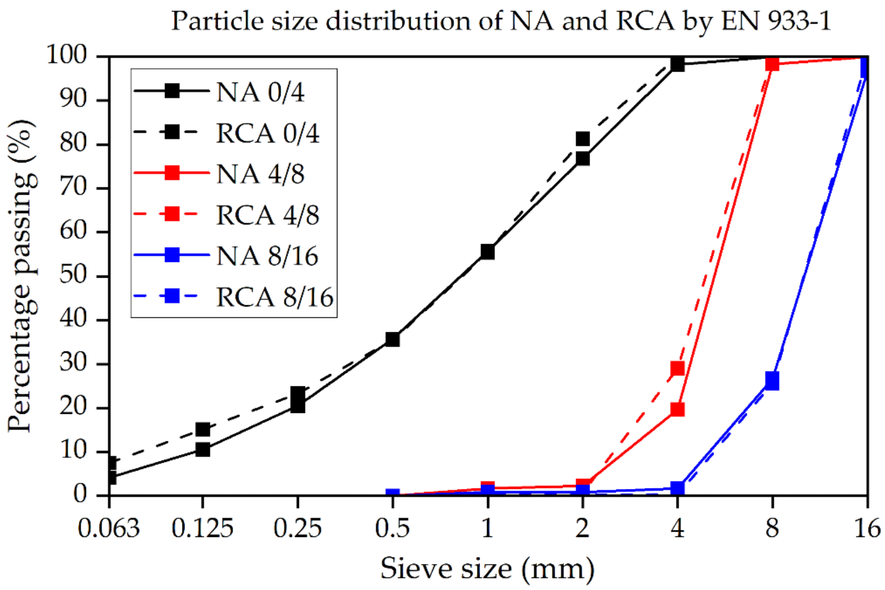


Figure 2. Particle size distributions of NA and RCA in accordance with EN standards

The basic difference between recycled and natural aggregates is the presence of old mortar attached to the recycled aggregate (Figure 3) [29]. The presence of old mortar, which is a part of the recycled aggregate, significantly influences the properties of both the recycled aggregate and the resulting fresh and hardened concrete. Specifically, the amount of adhered old mortar has a notable influence on the density and water absorption characteristics of recycled aggregates. Zega et al. (2010) studied the effect of different types of coarse aggregates and water-to-cement (w/c) ratios on the properties of recycled aggregates [30].

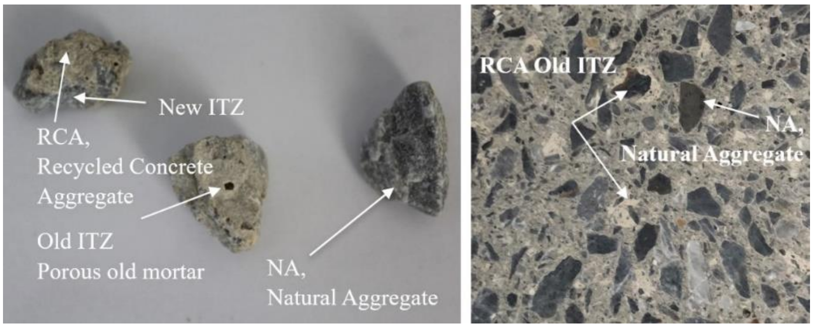


Figure 3. a) Recycled aggregate, and b) pictorial representation of concrete cross-section with NA and RCA

The grading of the recycled aggregate did not depend on the w/c ratio of the concrete from which the recycled aggregate was derived nor on the shape and texture of the parent concrete aggregate [28, 29]. In a concrete system, the use of RCA with a surface containing adhered mortar layers creates two types of interfacial transition zones (ITZs): an old ITZ zone and a new one, as shown in Figure 3. The ITZ is the region of cement paste around the aggregate particles that is perturbed by the presence of the aggregate. Its origin lies in the packing of cement grains against the much larger aggregates, leading to a local increase in the porosity and the predominance of smaller cement particles in this region. The porosity distribution in the new ITZ is significantly influenced by the initial moisture condition of the RCA and the strength of the RCA source concrete [14].

3. Concrete Mix Design

The reference concrete mixture Mix I: NA+0% RCA was prepared by applying an effective water-to-cement ratio of 0.53 and a cement content of 340 kg/m^3. The other mixes were designed using the same amount of cement and an effective water-to-cement ratio of 0.53, with varying amounts of water for each mix. The amount of added water was the amount necessary to be absorbed by the RCA, i.e., the amount of water that does not participate in the cement hydration process according to the EN 206 standard [27]. Therefore, it was not considered in determining the w_{eff}/c ratio. Figure 4 shows an overview of the constituent components in the concrete mixes.

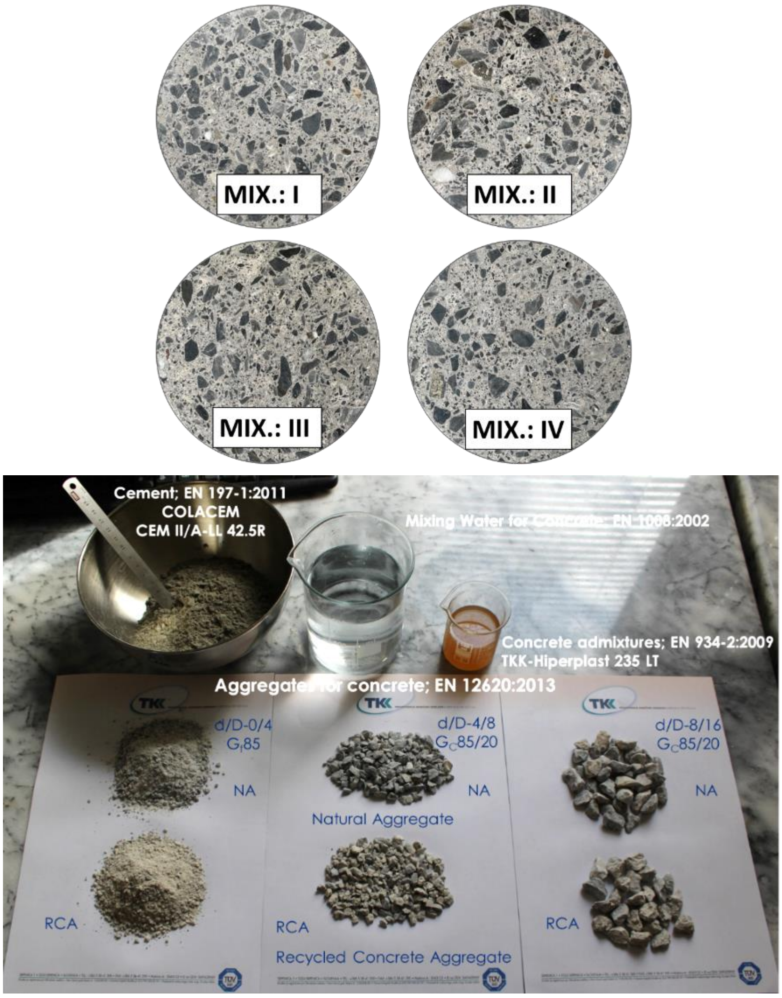


Figure 4. Constituent materials in concrete mixes

Figure 5 shows the optimal granulometric curves of the mixtures for all mix designs. A careful observation of the optimal granulometric curves of the mixtures revealed that they followed the same trend in almost all the cases. This has more to do with the similarity of the fractions and their granulometry because they were broken using the same stone crusher (see Figures 2 and 5). The Hiperplast 235 LT admixture content was increased from 0.4% for Mix I: NA+0% RCA up to 1.0% for Mix IV: NA+60% RCA, as shown in Table 6. This increase was made to maintain the consistency of the concrete. The properties of the concrete containing recycled aggregates were compared with those of the control concrete made of NA.

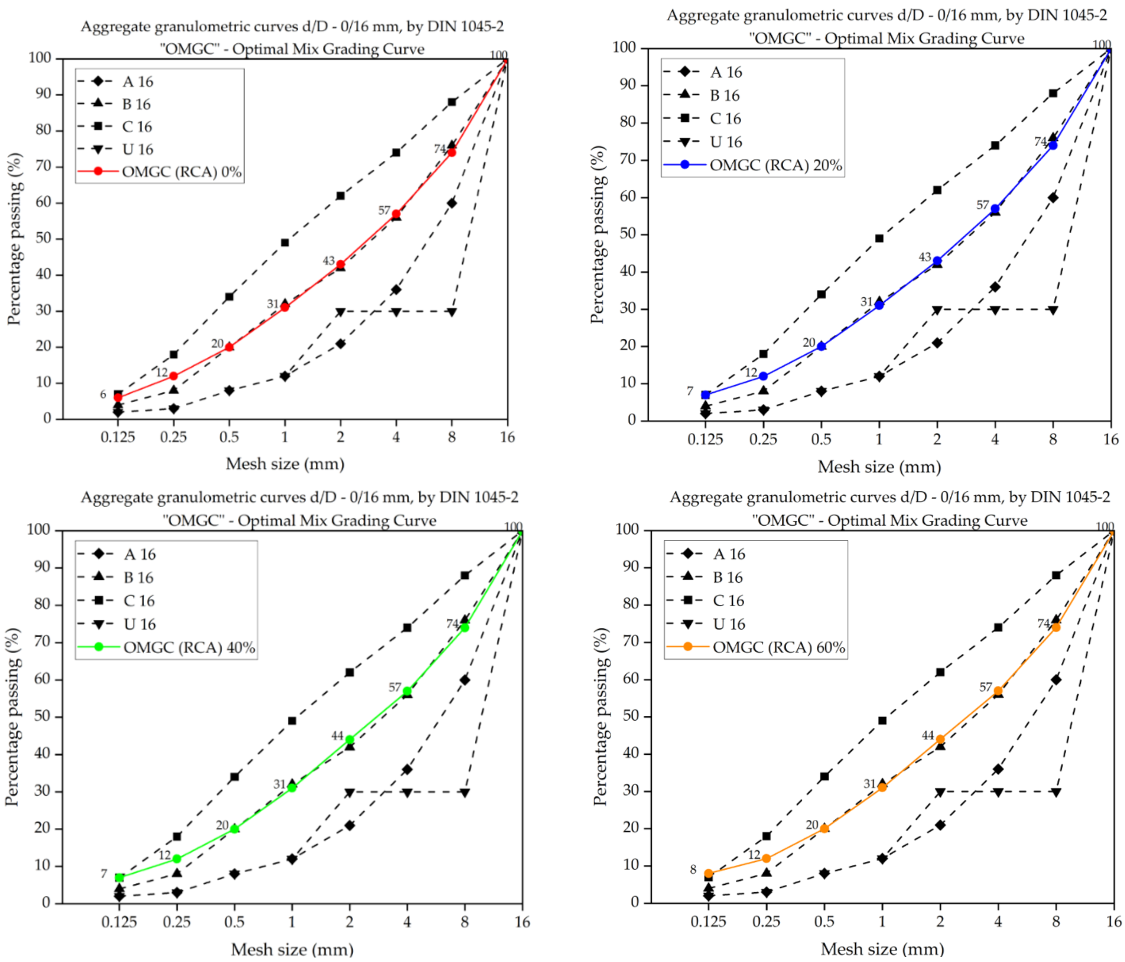


Figure 5. LG (OP) for all mix designs by DIN 1045-2 [31]

Table 6. Mixture proportions for all mix designs

Fraction: *d/D*	CEM II/A-LL 42.5 R (kg/m³)	Total water content (kg/m³)	Effective w_{eff}/c ratio	HiperPlast 235 LT (%)	Natural (or virgin) aggregate (NA), (kg/m³)			Recycled concrete aggregate (RCA), (kg/m³)		
					0/4	4/8	8/16	0/4	4/8	8/16
Mix I.: NA+0%RCA	340	189	0.53	0.40	1000	190	640	0.0	0.0	0.0
Mix II.: NA+20%RCA	340	201	0.53	0.55	800	152	512	200	38	128
Mix III.: NA+40% RCA	340	207	0.53	0.75	600	114	384	400	76	256
Mix IV.: NA+60% RCA	340	215	0.53	1	400	76	256	600	114	384

3.1.1. Properties of Fresh Concrete

Based on the work plan, all the concrete mixes were prepared with the same cement-to-concrete volume ratio. Initially, the mix design was prepared and mixed with the mix code I: NA+0% RCA, which was the mix containing only NA aggregates, with the following percentage of fractions: 0/4 = 55%, 4/8 = 10%, and 8/16 = 35%. Figure 5 shows the contents of such fractions in the other mixed compositions, such as Mix II: NA+20% RCA, Mix III: NA+40% RCA, and Mix IV: NA+60% RCA. The properties of fresh concrete with different percentages of RCA replacing NA were evaluated against those of standard concrete by examining the fundamental characteristics such as the consistency, air content, and density of the concrete. Once the concrete components were fully mixed, the resulting mixture reached a rheological state, which determines its plasticity. This state is crucial in different construction practices, including transportation, placement, compaction, and finishing, during the early stages and can influence the properties of hardened concrete. Since recycled aggregates from RCA differ very little from NA, their inclusion in the mix should not significantly change the properties of fresh concrete prepared using RCA; this, however, remains to be seen.

3.1.2. Workability/Slump Behavior

The workability of fresh concrete is an important property that controls the various other properties of concrete in its fresh and hardened states, such as density, air content, and strength. Workability is a property of concrete in its fresh state and includes batching, mixing, placing, compacting, and finishing operations. The workability of concrete depends on the properties of its constituents. The workability of concrete containing RCA has been widely studied because the various properties of RCA that control the workability of concrete do not match those of NA. Concrete made with RCA has a lower slump than that made with NC at the same w/c ratio [14]. The workability of concrete can be determined using various methods, the most versatile of which is the slump test. With regard to workability, various authors have discussed the role or influence of chemical additives. Because of the relatively high-water absorption of RCA and sometimes rougher surfaces, more water is required to maintain the same maneuverability as that observed under an equivalent NA composition. By controlling the quantity of the superplasticizer, it is possible to obtain a concrete mix with the same total w/c ratio as that of the control NA and to compensate for a part of the loss in compressive strength owing to the use of RCA [32]. The reviews presented in this paper were conducted according to the theory reported by Prakash and Krishnaswamy. Figure 6 shows the process of mixing the concrete and measuring its temperature using a digital thermometer.

Figure 6. Actual image of mixing concrete using a laboratory mixer and measuring the temperature of fresh concrete

3.1.3. Consistency of Concrete

The consistency of concrete refers to the aspect of workability that represents the following features of concrete in its fresh state. For most common applications, the consistency is specified by the slump class, which is measured using the slump test in accordance with EN 12350-2 [33]. The consistency is a measure of the wetness of a concrete mixture, which is commonly evaluated in terms of the slump (i.e., the wetter the mixture, the higher the slump) [34]. In this study, concrete mixes were prepared under laboratory conditions in the RH range of 55%–60% and air temperature (T_{air}) range of 20–23 ℃. Generally, each time after mixing the concrete, the temperature of the fresh concrete was first measured, which showed values from $t_{f.conc.} = 18.4$ ℃ to $t_{f.conc.} = 23$ ℃.

The consistency of the concrete was measured using the slump test method in accordance with the EN 12350-2 standard [33]. Time steps T0 (initial state), T1 = 30 min, and T2 = 60 min were used to observe the loss of consistency as a function of time. Figure 7 shows images corresponding to different moments during the consistency measurement for mix IV: NA+60% RCA. Table 7 presents the measured consistency values for all the mixtures.

Figure 7. Measurement of concrete consistency at times T0, T1, and T2, which correspond to the initial slump, slump after 30 min, and slump after 60 min, respectively

Table 7. Measured consistency values of all the mixtures in accordance with EN 12350-2 [33]

Slump (mm)	Mix I.: NA+0%RCA	Mix II.: NA+20%RCA	Mix III.: NA+40%RCA	Mix IV.: NA+60%RCA
T0 - Initial slump	210	220	220	220
T1 - After 30 min	170	180	160	150
T2 - After 60 min	140	150	130	110

3.1.4. Air Content

Typically, the appearance of air bubbles in fresh concrete can be attributed to the presence of air in the mixing water and the energy produced during the mixing operations, which is likely to create a liquid–air interface [34]. In this study, the air entrapped in the concrete mix was determined using the manometer method described in EN 12350-7 [35] and measured immediately after mixing. The test involved placing the concrete sample (Figure 8) with an unknown volume of air in a sealed air chamber, which was used to apply a known volume of air and pressure.

Figure 8. Air entrainment meter employed in the test in accordance with EN 12350-7 [35]

Figure 9 shows the porosity value of the concrete with an air content of 1.8% for mix II: NA+20% RCA. The higher air content in the recycled concrete mixtures is typically attributed to the presence of adhered mortar; this is because a higher porosity favors the occlusion of air in its pores (Kobayashi and Kawano, 1988). In our case, we did not observe any significant change in the air content. This is because during concrete preparation, the consistency of the concrete was maintained at the same level by adding a higher amount of the admixture (Hiperplast 235 LT). Figure 9 shows a graph of the values of the air content in all the examined concrete mixes.

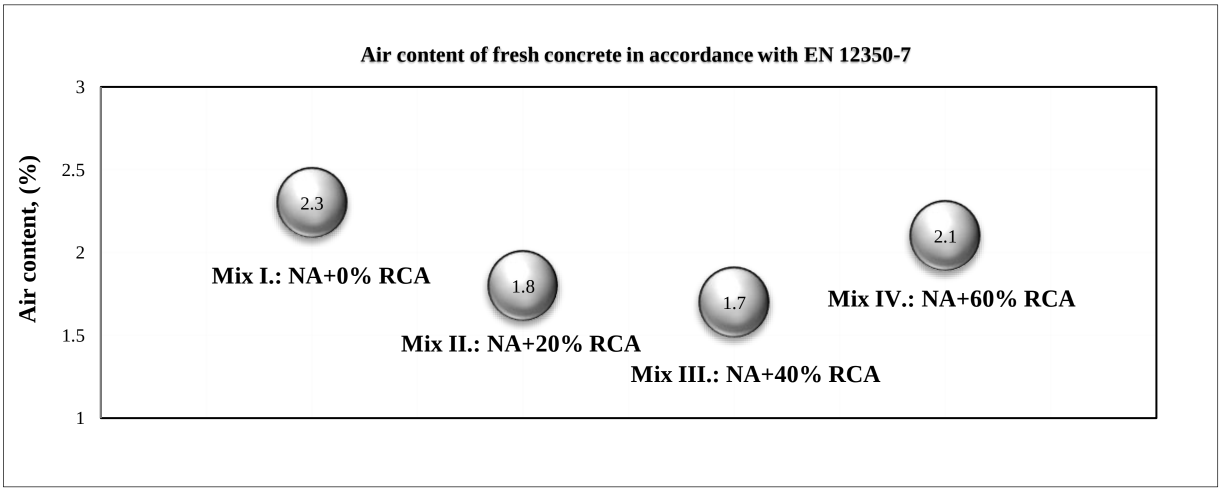


Figure 9. Values of the air content in concrete with and without RCA

3.1.5. Density of Fresh Concrete

The density of fresh concrete is a parameter that can be used to determine whether a concrete mix is appropriately designed. The unit weight or density of typical concrete is approximately 2400 kg per cubic meter. According to EN 206, normal-weight concrete is defined as concrete under oven-dry conditions with a density greater than 2000 kg/m^3 but not exceeding 2600 kg/m^3 [28]. In this study, the fresh densities of all the mixtures were determined in accordance with EN 12350-6 [36]. The specific values were 2310, 2330, 2360, and 2370 kg/m^3 for Mix IV: NA+60%RCA, Mix III:

NA+40%RCA, Mix II: NA+20%RCA, and Mix I: NA+0%RCA, respectively. This shows that increasing the RCA content in the concrete decreases the density of fresh concrete. Table 8 shows the fresh density values of each concrete mixture prepared in the study as well as the relative reduction in the density of the recycled concrete mixtures compared with the conventional concrete used as a reference. Figure 10 shows actual images of the testing and curing processes of the specimens.

Table 8. Fresh density values of concrete mixtures

	Density (kg/m^3)	Relative reduction (%)
Mix I: NA + 0%RCA	2374	/
Mix II: NA + 20%RCA	2362	0.5
Mix III: NA + 40%RCA	2333	1.7
Mix IV: NA +60%RCA	2311	2.7

Figure 10. Preparation and curing of the specimens for strength tests

3.1.6. Properties of Hardened Concrete

Concrete is a multiphase material containing cement paste (unhydrated and hydrated compounds), fluids, aggregates, and discontinuities. The overall mechanical and physical properties of such a composite system depend on the volume fractions and properties of the different constituents and the mechanisms of interaction, whether mechanical, physical, or chemical, between the separate phases [37]. In the following, we consider the properties of hardened concrete with and without the RCA, including its density, compressive strength and tensile splitting strength.

3.1.7. Compressive Strength of Test Specimens

Whenever the strength is used as the basis for the acceptance of concrete, specimens should be cast and cured in accordance with EN 12390-2 [38] for all mixes, as planned in this study. In accordance with the EN 12390-2 standard, eight concrete cubes with dimensions of 150 mm × 150 mm × 150 mm were used for each mixture, as shown in Figure

10. After 24 h, all the specimens were placed in a hardening bath at a temperature of 20±2 °C, where they were stored until the day of the test. Based on the test plan and in compliance with the EN 12390-3 standard, two cube specimens were examined after three days of casting, another two after seven, and two others after 28 days (Figure 11). The results for all specimens examined in compressive strength are expressed as average values (Figure 12). It should be noted that two of the eight specimens for each mixture were tested after 28 days for tensile splitting strength according to EN 12390-6 [39], the obtained results are expressed as an average value.

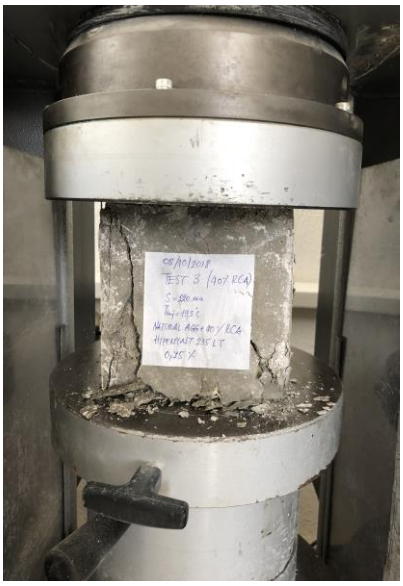


Figure 11. Compressive strength after 28 days of curing in accordance with EN 12390-3 [40]

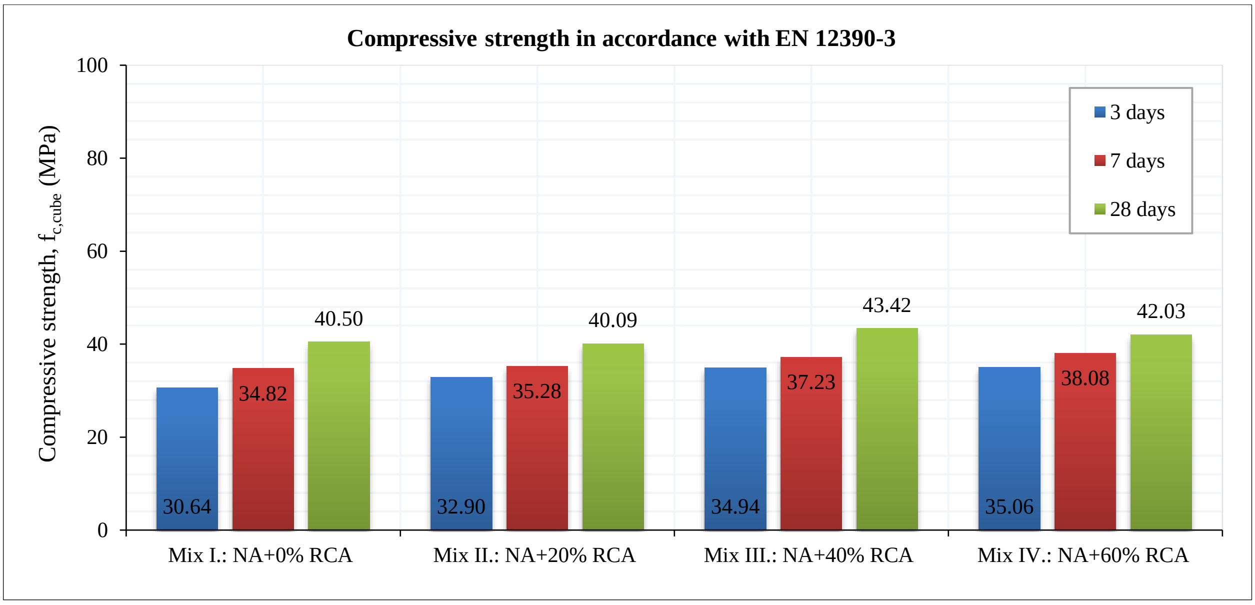


Figure 12. Graphical representation of results of the concrete compressive strength for all the mix-designs

3.1.7. Tensile Splitting Strength

The direct tensile strength is rarely determined by testing, and there is no European or International Standard. Nevertheless, when the tensile strength is determined by a tensile splitting test, in accordance with EN 12390-6 [40], EN 1992-1-1 allows tensile strength calculation from the tensile splitting strength $f_{ct,sp}$, as follows [41]:

$$f_{ct} = 0.9 \times f_{ct,sp} \quad (1)$$

A tensile splitting strength test was performed on hardened concrete to determine its tensile strength. Concrete cube specimens were tested in accordance with EN 12390-6 [40] (Figure 13). After 28 days of hardening in the bath, the concrete specimens were fully cured, removed from the water, and prepared for the tensile splitting strength test. Before the tests were conducted in compliance with the EN 12390-7 [42] standard, the density of the hardened concrete was determined. Table 9 presents the obtained values.

Figure 13. Images of the tensile splitting strength test conducted on the specimen

Table 9. Physicomechanical properties of hardened concrete after 28 days

Mix design	Mass of the specimen m (g)	Density of the hardened concrete *D* (kg/m³)	Tensile splitting strength $f_{ct,sp}$ (MPa)
Mix I: NA+0%RCA	8012	2374	3.58
Mix II: NA+20%RCA	7982	2365	3.73
Mix III: NA+40%RCA	7871	2332	2.93
Mix IV: NA+60%RCA	7802	2312	2.64
Minimum value	7802	2312	2.64
Maximum value	8012	2374	3.73
Average	7917	2346	3.20

The tensile splitting strength can be obtained using the formula [40]:

$$f_{ct} = \frac{2 \cdot F}{\pi \cdot L \cdot d} \quad (2)$$

where f_{ct} is the tensile splitting strength in MPa or N/mm², F is the maximum load, in N, L is the length of the line in contact with the specimen (mm), d is the designated cross-sectional dimension in mm.

Table 9 presents the results of the mass of the specimen, density and tensile splitting strength of the hardened concrete.

4. Discussion

In this section, we present and discuss the test results. The experimental results place particular emphasis on examining how the combined use of RCA and NA affects the characteristics of fresh and hardened concrete.

4.1. Slump Test

The consistency values of all the mixtures remained consistent throughout the testing, with no significant deviations from the design requirements. The loss of consistency from production time T0 to 60 min was within the standard requirements. At T0, all the measurements indicated that the consistency of the concrete reached the upper limit of class S4 in accordance with EN 206. However, there was a loss of consistency after 30 min. Mixes I and II had a loss of 40 mm, whereas Mixes III and IV had losses of 60 and 70 mm, respectively. These results were obtained by comparing the results for each mixture. After 60 min, the concrete with 60% RCA exhibited the greatest loss of consistency, changing from class S4 to class S3. Mix III, with 40% RCA, had a loss of 41%, corresponding to the S3 class, whereas Mix II had a loss of 31.8%, exceeding 220 mm. At T0 at 150 mm after 60 min, Mix I (NA + 0% RCA) showed a loss of 33.3%, also corresponding to consistency class S3. The greater water absorption capacity of the RCA had a significant impact on the water added to the mix, which can affect the workability of concrete, as shown in Nistratov et al. [43] and Matias et al. [44]. According to the American Concrete Institute (ACI) guidelines for the design of concrete mixes (ACI Committee 211, 2002), the air content expected for mixes containing 215 kg/m³ of water and a maximum aggregate size of 20 mm is approximately 2.00%, as indicated in Rodríguez [45].

4.2. Air Content

The volume of concrete mortar plays an important role in determining the air content. Because the RCA has a higher mortar content, it affects the air content in the concrete. Thus, when selecting the target air content of the RCA concrete, the existing air content of the mortar must be considered. Based on the particle sizes (granulometry) presented in this study, the air content of the mixtures remained the same in all the cases. Therefore, the air content of the concrete depends on the grain size of the aggregates and the degree of compression. Although RCA was used in the concrete mix, the air content was lower than that of the concrete made with NA. In Mix II, for example, the air content was 0.5%, which was lower than that of Mix I, whereas in Mix III, it was 0.6% lower than that of Mix I and 0.2% lower than that of the concrete made of only NA.

4.3. Density of Hardened Concrete

The density or unit weight of the hardened concrete decreased for mixtures with RCA compared with concrete containing NA, while in Mix I the value of density is D = 2374 kg/m^3, an almost negligible decrease was observed in the case of Mix II with only 9 kg/m^3 less than Mix I, whereas Mix III and Mix IV with 32 kg/m^3 and 62 kg/m^3 respectively, less compared with Mix I.

4.4. Compressive Strength

The compressive strength results showed that the early strength or three-day strength exhibited an increase of 14.4% in Mix IV compared with Mix I, an increase of 14.03% in Mix III compared with Mix I, and an increase of 7.37% in Mix II. After seven days, there was still an increase but with a lower growth rate. Thus, Mix IV showed an increase of 9.36%, Mix III showed an increase of 6.92%, and Mix II showed an increase of 1.32% compared with Mix I. The 28-day compressive strength showed largely the same result for all the mixtures; a slight difference was observed in Mix III compared with the other mixtures. This increase was approximately 7.2% compared with Mix I.

4.5. Tensile Splitting Strength

Depending on the requirement, it may be necessary to increase or decrease the tensile strength. For example, a high tensile strength is required to resist cracking. The factors influencing the tensile strength are as follows:

Compressive strength: Typically, the tensile strength varies proportionally with the compression (this assumption does not apply in the case of concrete containing RCA). The relative volumes of the cement paste and aggregate have little effect on the tensile strength (this assumption does not apply in the case of concrete containing RCA).

Coarse aggregate type: Concrete containing high-quality crushed rock coarse aggregates tends to have a higher tensile strength than concrete prepared with RCA. However, crushed RCA can result in a low tensile strength owing to the poor bonding between the RCA and NA surfaces. The tensile splitting strength results showed that the mixtures with RCA generally exhibited a lower tensile splitting strength owing to the lower adhesion of the aggregate particles to the cement matrix. Mix I showed that NA was better than RCA. Thus, Mix II with 20% RCA showed a slightly higher value, almost equal to that of Mix I with NA, whereas Mixes III and IV exhibited a decrease in resistance of 18.15% and 26.25%, respectively, compared with that of Mix I.

5. Conclusions

The use of RCA in concrete mixes resulted in a decrease in the unit weight or density of fresh concrete, primarily because of the higher water content of RCA concrete resulting from the absorption capacity of the RCA.

Our tests indicated that the replacement of normal aggregates with recycled aggregates generally brought about a slight improvement in the overall performance of the concrete. However, the tests also revealed that increasing the percentage of recycled aggregates in the mix can lead to a significant reduction in workability, a slight decrease in the tensile strength, and only a slight improvement in the compressive strength.

At a constant degree of workability or slump class, the amount of water required for the concrete mix based on RCA was approximately 6% to 14% higher than that required for the concrete mix without RCA. The consistency values of the concrete for all the mixes were consistent throughout the tests, and the loss of consistency between the production time and after 60 min was within the standard requirements.

Increasing the amount of superplasticizer admixture in the mix was found to improve the physicomechanical properties of the concrete, which helped mitigate the negative effects of using RCA. However, increasing the RCA content in the mix led to a deterioration in the splitting tensile strength of the concrete; this can be offset by increasing the amount of superplasticizer, which has shown to slightly increase the tensile and compressive strengths; the higher the water reduction power of the superplasticizer, the higher the concrete strength [44].

The results pertaining to the use of RCA as a partial replacement for NA may indicate that the RCA is an environmentally friendly material. It is nevertheless important to carefully consider the environmental impacts of the entire construction process, including transportation and other factors, to determine the true environmental impact of RCA usage. This study showed that the use of RCA in concrete mixes is a viable option for sustainable construction, provided good design and construction practices are followed.

6. Declarations

6.1. Author Contributions

Conceptualization, D.K. and F.S.; methodology, D.K. and F.S.; validation, F.S. and D.K.; formal analysis, A.M.; investigation, D.K.; resources, F.S. and D.K.; data curation, A.M. and I.K.; writing—original draft preparation, F.S.; writing—review and editing, F.S. and D.K.; visualization, I.K.; supervision, D.K.; project administration, F.S.; funding acquisition, F.S., D.K., A.M., and I.K. All the authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

The authors thank the management team of the company "VËLLEZËRIT E BASHKUAR" and IPE-PROING for their support in every stage of this study.

6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

7. References

[1] Eurostat. (2015). Generation of waste excluding major mineral wastes. Eurostat, Luxembourg City, Luxembourg. Available online: https://data.europa.eu/data/datasets/mk1igskoervru59fvpqcw?locale=en, (accessed on February 2023).

[2] International Energy Agency (IEA). (2020). Cement Technology Roadmap 2020. Available online: https://www.iea.org/ (accessed on March 2023).

[3] UNEP. (2022). 2022 Global Status Report for Buildings and Construction. United Nations Environment Programme (UNEP), Nairobi, Kenya. Available online: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction (accessed on March 2023).

[4] Fetting, C. (2020). The European green deal. ESDN report, 53, ESDN Office, Institute for Managing Sustainability, Vienna University of Economics and Business, Vienna, Austria.

[5] International Energy Agency (IEA). (2018). Technology Roadmap – Low-Carbon Transition in the Cement Industry. International Energy Agency (IEA), Paris, France. Available online: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry (accessed on February 2023).

[6] Zhao, Y., Yu, M., Xiang, Y., Kong, F., & Li, L. (2020). A sustainability comparison between green concretes and traditional concrete using an emergy ternary diagram. Journal of Cleaner Production, 256. doi:10.1016/j.jclepro.2020.120421.

[7] EN 197-1:2011. (2011). Cement Part 1: Composition, specifications, and conformity criteria for common cements. European Standard, Brussels, Belgium.

[8] Mohammed, A. H., Mubarak, H. M., Hussein, A. K., Abulghafour, T. Z., & Nassani, D. E. (2022). Punching Shear Characterization of Steel Fiber-Reinforced Concrete Flat Slabs. HighTech and Innovation Journal, 3(4), 483-490. doi:10.28991/HIJ-2022-03-04-08.

[9] EN 1008:2002. (2002). Mixing water for concrete-Specification for sampling, testing, and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete. European Standard, Brussels, Belgium.

[10] Kosmatka, S. H., & Wilson, M. L. (2011). Mixing Water for Concrete. Design and Control of Concrete Mixtures (15^{th} Ed.), Portland Cement Association, Skokie, United States.

[11] EN 934-1:2008. (2008). Admixtures for concrete, mortar, and grout — Part 1: Common requirements. European Standard, Brussels, Belgium.

[12] EN 934-2:2009. (2009). Admixtures for concrete, mortar, and grout — Part 2: Concrete admixtures — Definitions, requirements, conformity, marking and labelling. European Standard, Brussels, Belgium.

[13] EN 12620:2013. (2013). Aggregates for concrete. European Standard, Brussels, Belgium.

[14] Verian, K. P., Ashraf, W., & Cao, Y. (2018). Properties of recycled concrete aggregate and their influence in new concrete production. Resources, Conservation and Recycling, 133, 30–49. doi:10.1016/j.resconrec.2018.02.005.

[15] Snyder, M. B., Vandenbossche, J. M., Smith, K. D., & Wade, M. (1994). Synthesis on Recycled Concrete Aggregate. Interim Report-Task A. Federal Highway Administration (FHWA), Washington, DC.

[16] Verian, K. P. (2012). Using recycled concrete as coarse aggregate in pavement concrete. Doctoral dissertation, Purdue University, IN, United States.

[17] Verian, K. P., Whiting, N., Olek, J., Jain, J., & Snyder, M. (2013). Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost. doi:10.5703/1288284315220.

[18] Li, X. (2009). Recycling and reuse of waste concrete in China. Resources, Conservation and Recycling, 53(3), 107–112. doi:10.1016/j.resconrec.2008.11.005.

[19] Wen, H., McLean, D. I., & Willoughby, K. (2015). Evaluation of Recycled Concrete as Aggregates in New Concrete Pavements. Transportation Research Record: Journal of the Transportation Research Board, 2508(1), 73–78. doi:10.3141/2508-09.

[20] Yehia, S., & Abdelfatah, A. (2016). Examining the variability of recycled concrete aggregate properties. In Proceedings of the International Conference on Civil, Architecture and Sustainable Development (CASD-2016), London, UK.

[21] Hansen, T. C., & Narud, H. (1983). Strength of recycled concrete made from crushed concrete coarse aggregate. Concrete international, 5(1), 79-83.

[22] R.S. Ravindrarajah, & C.T. Tam (1985). Properties of concrete made with crushed concrete as coarse aggregate. Magazine of Concrete Research 37 (130), 29-38.

[23] Ait Mohamed Amer, A., Ezziane, K., Bougara, A., & Adjoudj, M. (2016). Rheological and mechanical behavior of concrete made with pre-saturated and dried recycled concrete aggregates. Construction and Building Materials, 123, 300–308. doi:10.1016/j.conbuildmat.2016.06.107.

[24] Kurda, R., de Brito, J., & Silvestre, J. D. (2017). Influence of recycled aggregates and high contents of fly ash on concrete fresh properties. Cement and Concrete Composites, 84, 198–213. doi:10.1016/j.cemconcomp.2017.09.009.

[25] Liu, Q., Xiao, J., & Sun, Z. (2011). Experimental study on the failure mechanism of recycled concrete. Cement and Concrete Research, 41(10), 1050–1057. doi:10.1016/j.cemconres.2011.06.007.

[26] Kryeziu, D. R., Muja, A., Kadiu, F., Krelani, V., Sinani, B., & Qafleshi, M. (2018). Green Concrete made with Recycled Concrete Aggregates: Fresh and Hardened Properties. 2018 UBT International Conference. doi:10.33107/ubt-ic.2018.51.

[27] EN 206:2013. (2013). Concrete-Specification, performance, production and conformity. European Standard, Brussels, Belgium.

[28] Benalia, S., Zeghichi, L., & Benghazi, Z. (2022). A Comparative Study of Metakaolin/Slag-Based Geopolymer Mortars Incorporating Natural and Recycled Sands. Civil Engineering Journal, 8(8), 1622-1638. doi:10.28991/CEJ-2022-08-08-07.

[29] Rao, M. C., Bhattacharyya, S. K., & Barai, S. V. (2019). Systematic Approach of Characterisation and Behaviour of Recycled Aggregate Concrete. Springer Transactions in Civil and Environmental Engineering, Springer, Singapore. doi:10.1007/978-981-10-6686-3.

[30] Zega, C. J., Villagrán-Zaccardi, Y. A., & Di Maio, A. A. (2010). Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. Materials and Structures/Materiaux et Constructions, 43(1–2), 195–202. doi:10.1617/s11527-009-9480-4.

[31] DIN 1045-2;2008-08. (2008). Structures made of concrete, reinforced concrete and prestressed concrete - Part 2: Concrete - Specification, properties, production and conformity - Application rules for DIN EN 206-1, © DIN Deutsches Institut für Normung e. v, Berlin, Germany.

[32] Silva, R. V., De Brito, J., & Dhir, R. K. (2015). The influence of the use of recycled aggregates on the compressive strength of concrete: A review. European Journal of Environmental and Civil Engineering, 19(7), 825–849. doi:10.1080/19648189.2014.974831.

[33] EN 12350-2;2019. (2019). Testing fresh concrete — Part 2: Slump-test. European Standard, Brussels, Belgium.

[34] Mehta, P. K., & Monteiro, P. J. (2006). Proportioning Concrete Mixtures. Concrete Microstructure, Properties, and Materials (3rd Ed.), McGraw-Hill, New York, United States.

[35] EN 12350-7;2019. (2019). Testing fresh concrete — Part 7: Air content — Pressure methods. European Standard, Brussels, Belgium.

[36] EN 12350-6;2019. (2019). Testing fresh concrete — Part 6: Density. European Standard, Brussels, Belgium.

[37] Newman, J. (2003). Strength and failure of concrete under short-term, cyclic and sustained loading. Advanced Concrete Technology, 3–36, Butterworth-Heinemann, Oxford, United Kingdom. doi:10.1016/b978-075065686-3/50253-6.

[38] EN 12390-2:2019. (2019). Testing hardened concrete — Part 2: Making and curing specimens for strength tests. European Standard, Brussels, Belgium.

[39] EN 12390-3;2019. (2019). Testing hardened concrete — Part 3: Compressive strength of test specimens. European Standard, Brussels, Belgium.

[40] EN 12390-6:2019. (2019). Testing hardened concrete ― Part 6: Tensile splitting strength of test specimens. European Standard, Brussels, Belgium.

[41] Bamforth, P., Chisholm, D., Gibbs, J., & Harrison, T. (2008). Properties of concrete for use in Eurocode 2. A Cement and Concrete Industry Publication, The Concrete Center, London, United Kingdom.

[42] EN 12390-7:2019. (2019). Testing hardened concrete — Part 7: Density of hardened concrete. European Standard, Brussels, Belgium.

[43] Nistratov, A. V., Klimenko, N. N., Pustynnikov, I. V., & Vu, L. K. (2022). Thermal Regeneration and Reuse of Carbon and Glass Fibers from Waste Composites. Emerging Science Journal, 6(5), 967-984. doi:10.28991/ESJ-2022-06-05-04.

[44] Matias, D., De Brito, J., Rosa, A., & Pedro, D. (2013). Mechanical properties of concrete produced with recycled coarse aggregates - Influence of the use of superplasticizers. Construction and Building Materials, 44, 101–109. doi:10.1016/j.conbuildmat.2013.03.011.

[45] Rodríguez, D. (2016). Ceramic and mixed construction and demolition wastes (CDW): A technically viable and environmentally friendly source of coarse aggregates for the concrete manufacture. Ph.D. Thesis, Ghent University, Gent, Belgium.