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Orginal Article

Physical and mechanical behaviour of recycled concrete under destructive and non-destructive testing

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Abstract: Aggregates recycled from construction sites may exhibit slightly inferior characteristics compared to natural aggregates in terms of porosity, friability, and variability. However, it must be acknowledged that although recycled aggregates are currently used only in small proportions for manufacturing concrete, their usage is steadily increasing. It is now widely recognised that the reuse of recycled aggregates in mortar and concrete significantly contributes to the preservation of alluvial aggregates. The valorisation of recycled aggregates in concrete and mortar offers a clear economic advantage in the construction sector. Indeed, the reuse of materials from demolition could be envisaged directly on site or at construction waste recycling and treatment platforms. Additionally, it should be noted that to date, there is no specific standard for measuring the water absorption of recycled aggregates. Regarding the physical properties, the estimation of the absorption kinetics of the recycled aggregates has proved necessary. Moreover, other equally important measurements must be undertaken to determine all the other properties. The results obtained demonstrated that a good correlation exists between the substitution rate and the physical and mechanical properties of the prepared concrete. Furthermore, it was decided to vary the substitution rate of natural sand with recycled sand during the manufacture of concrete according to the following percentages: 25% recycled sand with 75% natural sand, and 50% recycled sand with 50% natural sand.

Keywords: concrete; recycled gravel; recycled sand; physical tests; non-destructive testing

1. Introduction

The construction sector annually generates millions of tons of construction and demolition waste, predominantly consisting of inert waste that poses no harm to human health or the environment. However, initiatives for recovering this waste are currently scarce. Once this waste is recovered using recycling devices, it can be utilized as an alternative material to replace natural aggregates in the construction sector [1–8].

Interest in developing this waste recovery technique arises in response to alarming observations about the scarcity of natural resources, the nuisances caused by waste dumping, and the constantly increasing management costs associated with them.

Similarly, recycling and utilizing waste from construction sites significantly reduces the quantities of waste destined for landfills or incinerators. However, these methods have proven insufficient in handling the progressively increasing production of waste by the building sector. For instance, Quebec witnessed an increase in the recycling rate from 18% to 42% between 1988 and 2002 [9], and from 52% to 64% between 2006 and 2019 [10]. This coincides with a rise in waste production per inhabitant, increasing from 640 to 870 kg/year/person. Similarly, waste volume in France doubled between 1980 and 2005, reaching 360 kg/year/person [11].

Notably, specialists in the construction field began seriously considering the recycling of demolition and construction waste at the beginning of the 21st century. Subsequently, elaborate legislation was enacted to regulate waste production, storage, treatment, and recycling. Hazardous waste incineration was addressed by Directive No. 2000/76/EC of the European Parliament and the Council on December 4, 2000. Storage of special industrial waste is controlled by Directive No. 1999/31/EC of April 26, 1999, on the landfilling of waste, and by Commission Decision No. 2000/532/EC of May 3, 2000, along with Council Decision 94/904/EC, establishing a list of hazardous waste [12].

Ultimately, mortar and concrete design is a complex process that requires a thorough evaluation of the materials used, project requirements, and expected performance. Civil engineers and building materials experts play a vital role in formulating appropriate mixtures for each application, taking into account factors such as mechanical strength, durability, and resistance to aggressive environments.

Concrete formulation approaches are numerous and set specific parameters to compare and observe the effects of recycled aggregates on the physical behavior of manufactured concretes. Some researchers, such as Debieb et al. and Levy and Helene [13, 14], chose to work with constant workability, while others, like Gómez-Soberón and Evangelista and de Brito [15, 16], focused on mixing time, the degree of humidity of recycled aggregates, and both the overall and actual water quantities to be used.

Moreover, the replacement of cement or natural aggregates in concrete composition can involve either mass or volumetric replacement, while other parameters remain unchanged [17]. Finally, some researchers have preferred working with the concrete equivalent mortar (CEM) method, considering the cementitious matrix present in recycled aggregates in the newly formulated concrete's cementitious matrix [18–20].

Today, there is no universally recognized concrete composition method deemed the best. The concrete composition always results from a compromise between generally contradictory requirements. A concrete composition method could be considered satisfactory if it allows the production of concrete that meets project contract specifications. Several experimental studies have shown that grain size distribution and maximum aggregate size impact aggregate proportions, binder and water quantities required, workability, porosity, shrinkage, and concrete durability. Any variation in particle size distribution significantly affects concrete uniformity across batches. It is worth mentioning that very fine sands are often uneconomical, while coarse sands and granulates can produce stiff, unwieldy mixes.

According to Mehta and Monteiro [21], aggregates with neither excessive nor deficient particles of a given diameter, presenting a regular granulometric curve, yield the best results. Heterogeneity in particle size significantly reduces the total void volume between aggregates [22].

Furthermore, several researchers have shown interest in the issue. Sri Ravindrarajah [23] demonstrated that the type of crusher and the quality of recovered concrete both influence the consistency of granulometric curves in prepared concretes. Weimann et al. [24] established that wet stripping virtually eliminates contamination by undesirable elements (wood, metal, and non-concrete constituents). However, it is noteworthy that these elements remain below 2%. Additionally, concrete containing recycled sands exhibits a weaker cementitious matrix over time.

On the contrary, Evangelista De Brito [15] conducted a study revealing that recycled aggregates are generally more angular, thus possessing greater internal friction and absorption. This results in a higher water demand for concrete with the same curve and equal fineness modulus [25].

In addition, Jemmali's results [26] indicated that aggregates with a high proportion of flat and elongated particles are challenging to compact and exhibit a higher intergranular void index compared to aggregates with more rounded particles. The void ratio of the granular mixture is a critical parameter for concrete formulation, impacting properties like compactness, workability, and mechanical properties.

According to Jemmali [26], careful attention must be paid to the characteristics of the granular mixture, as a high void ratio mix yields less economical concrete, requiring more cementitious materials to meet performance requirements (workability, mechanical properties, permeability, durability). In general, the most advantageous aggregates for concrete formulation are those with high proportions of cubic particles (enhancing granular skeleton compactness) and rough particles (improving paste-aggregate adhesion). It was found that the shape and roughness of aggregates can hinder air bubble extraction during vibration, leading to slightly higher levels of entrained air in concretes containing recycled aggregates [27], cited by Topçu and Canbaz [28], with a difference of about 0.6%.

Moreover, recycled aggregates obtained by crushing exhibit high surface roughness and relatively low compactness. This new recycling approach increases the effective water amount introduced into the concrete. The total water demand for concrete preparation can be higher because recycled aggregates absorb a large quantity of water. If the stored aggregates are not saturated, water absorption from the aggregates occurs in the hours following mixing [25].

The granularity of aggregates can lead to high fine particle contents, especially when using recycled sand. Foundry sands, well-known by-products of the foundry industry, can also be recycled. After reaching their reuse limit in the foundry industry, they are destined for landfill, presenting an opportunity as a raw material for hydraulic concrete manufacture [29]. Aggregates from demolition concrete or other construction waste can be recovered for hydraulic concrete production and extended to other uses. Despite numerous research studies, recycled aggregates find limited applications as concrete aggregates. Comparative studies have shown that recycled aggregates from demolition can be added to conventional concrete for the preparation of new concretes [30].

According to Julien Navaro [31], manufacturing asphalt with half recycled bituminous products can reduce greenhouse gas emissions by 10% and save 40% of natural resources.

This confirms that recycling can be an effective solution for reducing the consumption of natural aggregates and bituminous binders from non-renewable natural raw materials.

Demolition waste from buildings can be categorized into three groups [32]:

- The first category comprises elements that can be directly valorised in their original form and function (e.g., beams, window frames).
- The second category includes elements that are recoverable after treatment or transformation (e.g., mineral rubble, metals).
- The third category consists of non-recoverable materials with a high content of pollutants that cannot be valorised.

The quality of recycled aggregates depends on their condition at demolition and any damage incurred during crushing and transportation [16, 33–35].

Our literature review revealed that to produce new concrete, recycled crushed concrete aggregates must exhibit a relatively high water absorption rate. Several authors have investigated the characteristics of recycled aggregates, which can originate from waste and by-products of concrete and mortars, as well as from unused or unusable batches of concrete. This waste accounts for 0.2 to 1% of the total concrete mass produced, depending on the industry sector. Additionally, defective or poorly formed products, partially broken items, or those not meeting appearance standards are included, accounting for 0.2 to 3% of waste, subject to sorting conditions [36].

The primary objective of this study is to conserve natural resources by substituting conventional building materials with materials recovered from construction waste. This approach will likely prompt legislators to develop robust regulations governing construction waste recycling, thereby preserving natural resources.

Our research aims to incorporate recycled aggregates into the formulation of a new type of concrete by replacing natural aggregates in proportions varying from 0 to 100%. Furthermore, to facilitate comparisons, control concretes were formulated to establish a baseline. Additionally, in practice, the concrete and construction industry take many variables into account to optimize the chemical and mechanical composition of concrete based on the intended application and specific project constraints.

Finally, to address our research question satisfactorily, we conducted destructive and non-destructive experimental tests on materials derived from recycled waste to evaluate the performance of concrete made with recycled components and estimate its mechanical strength.

2. Materials and tests

2.1. Measurement of density and absorption coefficient

The experimental program adopted in this research involves manufacturing road concrete based on recycled aggregates from concrete specimens and/or demolition concrete. The repeatability of measurements was achieved by conducting tests on the same batch three times consecutively.

The recorded observations indicated that the recycled aggregates (gravel fractions) were directly linked to the volume fractions of the constituents making up the paste. Similarly, the sand, whose characteristics indicated that the material was unusable in its current state, was subjected to the same tests to improve its properties, even at minimal percentages.

Subsequently, recycled aggregates were categorized into three classes: 0/5, 3/8, and 8/15. These were then incorporated into the mixes as a replacement for natural aggregates at various levels during the manufacturing of concrete, as detailed in Table 1. It should be noted that the nomenclature adopted here will be used to verify and compare the results obtained for the different batches.

Table 1. Rate of aggregates in mixes

Identifier	Designation	Incorporation rate [%]			
		Natural gravel	Recycled gravel	Sand from Terga	Sand from Sfisef
		NG	RG	ST	SF
OC	Ordinary concrete	100		100	
CR1	Recycled concrete 1	85	15	100	
CR2	Recycled concrete 2	70	30	100	
CR3	Recycled concrete 3	50	50	100	
CR4	Recycled concrete 4	20	80	100	
CR5	Recycled concrete 5	100		75	25
CR6	Recycled concrete 6	100		50	50

The produced concretes belong to class S3 and exhibit a slump ranging from 7 to 12 cm, all falling under class C25/30. Additionally, the cement dosage is 335 kg/m³. Subsequently, the obtained results were compared with those of the control concrete (without recycled aggregates). The behaviour of the formulated concretes was then examined in both the fresh and hardened states.

Regarding recycled materials, a re-evaluation of the problem is necessary since they were initially considered waste. To effectively utilize reusable materials, it is imperative to introduce materials that have undergone minimal transformation or alteration, forming a small portion of the recycled concrete composition.

However, this approach is intricate and requires a detailed examination of recycled materials at each manufacturing stage to minimize formulations that may yield unsatisfactory results.

In this study, cement (CPJ II) 42.5 was utilized along with a high water-reducing superplasticizer admixture provided by the manufacturer NEO QUIM. Recycled aggregates of classes 3/8, 8/15, and 15/25 were sourced from the concrete specimens. It's worth noting that the natural aggregates employed in this research also fall within the classes 3/8, 8/15, and 15/25.

Subsequently, measurements for density and absorption coefficient were taken at 24 hours. The drying process for the gravels involved the use of an absorbent fabric, a method also applied to sand, excluding light sand. This procedure entails the preparation of multiple batches by crushing 125 kg of aggregates according to Standard NF EN 932-2.

2.2. Characteristics of sand

The test recommended by Standard NF EN 933-1 enables the determination of the sizes and respective weight percentages of the different grains that make up the sample. Thus, the sample was passed through a series of sieves of decreasing sizes, from the largest to the smallest, and the residue retained on each sieve was weighed. The results of the particle size analysis of the local quarry sand are presented in Fig. 1.

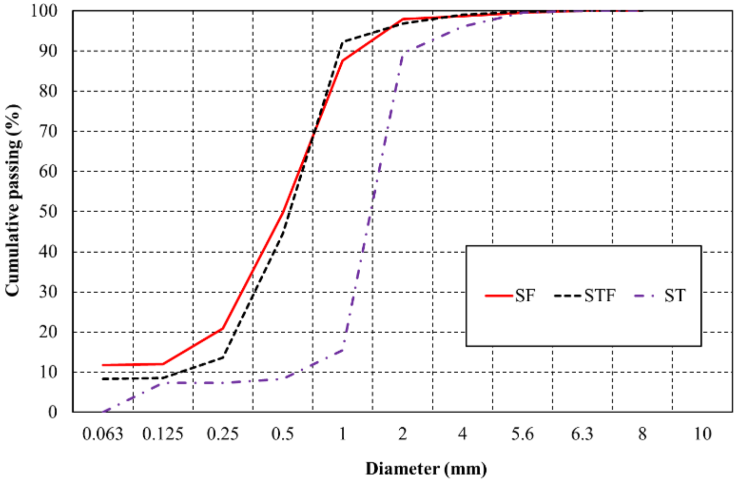

Fig. 1. Particle size distribution curves of sands

2.3. Characteristics of gravel

It is widely acknowledged that both natural and recycled aggregates must adhere to the criteria outlined in current standards to be deemed suitable for use. The specifications or characteristics of aggregates are regulated by standards and requirements that must be met. The fractions utilized include 3/8, 8/15, and 15/25. It is important to note that the recycling of waste materials serves two primary purposes: firstly, to reduce the quantities of waste in the environment, and secondly, to recover and utilize them as substitutes for natural materials, thereby reducing costs in the public works and construction sectors. The chemical characteristics of natural and recycled aggregates are summarized in Table 2.

Table 2. Chemical characteristics of natural and recycled aggregates

Borehole or well	Carbonates $CaCO_3$ (%)	Sulfates (%)	Chlorides (%)
Natural aggregate	96.99	None	0.42
Recycled aggregate	60.82	None	0.42

Following the NF P 18-560 standard, particle size analysis is conducted to determine the size and mass percentages of different grain classes in the prepared samples. The test involves classifying the sample's various grains using a series of nested sieves stacked atop one another, with openings that decrease in size from top to bottom. The material under examination is placed in the top sieve, and the different grain fractions are obtained by vibrating the sieve stack. It's important to note that the quantity of gravel used must meet various requirements to ensure sample representativeness and to avoid excessively long test durations and sieve saturation, which would render them inoperative. In practice, the mass used must adhere to the criterion: M > 0.2 Dmax. The results of the particle size analysis of the natural and recycled gravel are presented in Fig. 2 and Fig. 3, respectively.

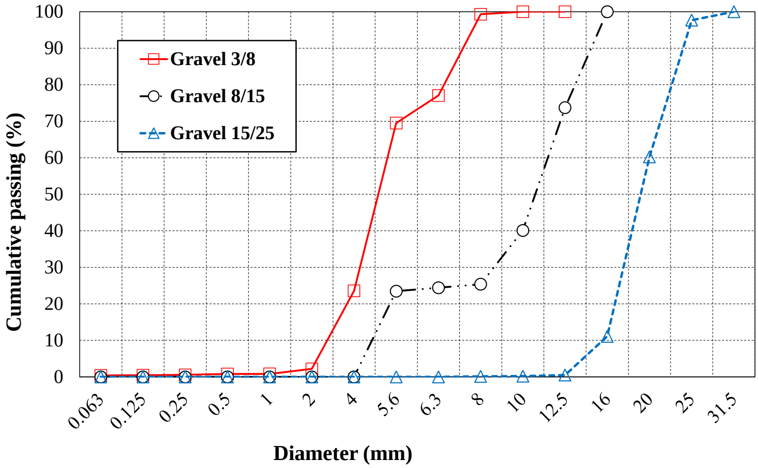

Fig. 2. Particle size distribution curves of natural aggregates

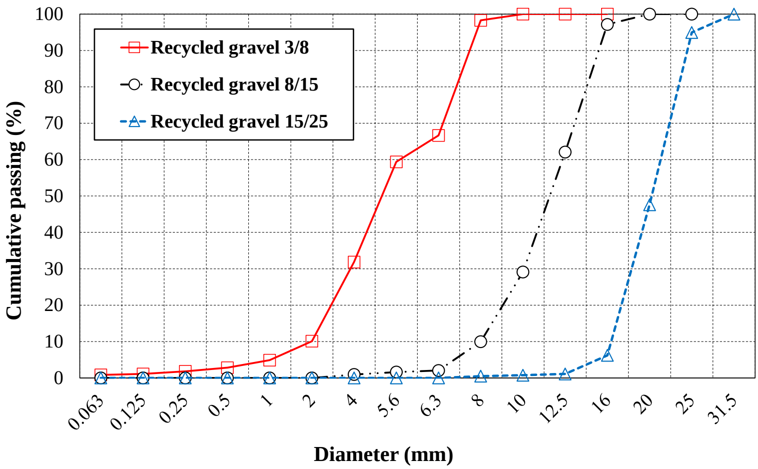

Fig. 3. Particle size distribution curves of recycled aggregates

The results obtained by Loranger within the framework of a study conducted on recycled materials have been confirmed by several researchers [37]. He found that the losses in the Los Angeles test varied between 28 and 32%. Additionally, the differences between the various mixtures were not very significant, which confirms the observations of Marquis et al. [38].

Mamery [19] examined the mechanical properties of demolition waste. He found that concrete made with this waste presented lower resistance to impact fragmentation compared to that with alluvial aggregates. For this purpose, the Los Angeles test was carried out in accordance with Standard NF EN 1097-1, to measure the resistance of gravel to impact fragmentation. The results are presented in Table 3. This test can be applied to aggregates of natural or artificial origin used in the field of building and public works. The principle of this test consists of estimating the quantity of elements of size less than 1.6 mm produced when the material is subjected to standardized ball shocks in the Los Angeles machine. This experimental study, in which the choice is made on the 10/14 fraction, applies to aggregates of natural or artificial origin.

The densities and water absorption coefficients of the recycled gravel were measured according to the method described in the standard EN 1097-6 for natural aggregates.
For each size of particle studied, five different test portions were tested. To test the repeatability of measurements, the same sample was tested three times in a row, under the same conditions, for each particle size.

The repeatability tests gave a relatively low standard deviation (< 0.3%) for the density measurements. However, this deviation was much higher for water absorption coefficient measurements (> 12%). The results are summarized in Table 3.

Table 3. Physical and chemical characteristics of natural and recycled sands and gravels

	Type of sand			Type of gravel					
	ST	SF	STF	NG			RG		
				3/8	8/15	15/25	3/8	8/15	15/25
Apparent density (kg/m^3)	1.12	1.08	1.13	1.39	1.35	1.29	1.30	1.24	1.11
Absolute density (kg/m^3)	2.59	2.60	2.64	2.63	2.67	2.73	2.63	2.69	2.82
Micro-Deval (%)					20.28			37.58	
Los Angeles (%)					21.74			32.60	
Sand equivalent (%)	75.84	28.85	49.31						
Methylene blue test	0.80	0.50	2.20						
Water content	0.20	0.30	0.20						
Fineness modulus	1.91	1.45	1.51						

2.4. Aggregate absorption kinetics

In traditional techniques, compact aggregates with an absorption rate below 1% are typically preferred. Under these circumstances, the impact of water absorption and initial saturation rate can be disregarded. However, sourcing such aggregates in sufficient quantities and at reasonable costs is becoming increasingly challenging, particularly in densely populated areas. The economic and environmental burdens associated with transportation, as well as the disturbances linked to quarry exploitation, significantly affect available resources. Consequently, builders are compelled to utilise relatively porous aggregates or recycled aggregates in the formulation of new concretes to mitigate the depletion of natural materials, which are becoming scarce. To address this, we endeavoured to determine the absorption rate of both natural and recycled aggregates by conducting a test involving the use of 1000 g of gravel for each fraction (3/8, 8/15, and 15/25), placed in a container filled with fresh water and left to stand for 24 hours.

It is worth mentioning that in order to be able to use these gravels, it is imperative to determine their density with high precision as well as their water absorption coefficient at 24 h. In addition, water absorption is not instantaneous, which means that we have to estimate the absorption kinetics of recycled aggregates.

In order to evaluate this kinetics, a procedure that is more elaborate than the standardised method and inspired by a process developed and described by Tam et al. was used [39]. Note that this method is similar to the standardised method applied to lightweight aggregates (appendix C EN 1097-6).

The measurements are performed in about ten minutes and are carried out over the long term. The absorption kinetics was conducted under the conditions recommended in appendix C of the standard under consideration.

It is important to note that precise determination of the density and 24-hour water absorption coefficient of these gravels is essential for their utilisation. Furthermore, as water absorption is not instantaneous, it is necessary to estimate the absorption kinetics of recycled aggregates. To evaluate this kinetics, a more sophisticated procedure, inspired by a method developed and described by Tam et al. [39], was employed. This method is like the standardised method applied to lightweight aggregates (appendix C EN 1097-6). Involves measurements conducted over a period of about ten minutes and is conducted under the recommended conditions outlined in Appendix C of the relevant standard.

2.5. Formulation of concrete

The Dreux-Gorisse method was used for the formulation of our concrete. For this, seven concrete mixes were prepared. The specimens used in this study have similar geometries. They were moulded according to the recommendations of the test to be carried out. Thus, cubic samples, with dimensions of (15x15x15) cm^3, were made to carry out the mechanical tests.

The performance required for construction concrete implies a consistency suitable for its use. It is usually defined using the Abrams cone sag test. In order to meet the requirements related to the mechanical tests that are most often carried out at 28 days (fc28), and for the purpose of achieving high durability, it is imperative to impose a minimum cement dosage Cmin and a maximum ratio (W/C).

The formulation of concrete must meet the first two requirements, namely strength and durability, at the lowest costs. However, the economic aspect should also play an essential role, hence the choice of our products which must firstly be local and secondly have to come from waste in order to achieve the desired objective. We therefore adopted the Dreux-Gorisse method to determine the composition of our concrete.

The workability of the manufactured concrete was as required by the Standard in force. Afterwards, the results obtained experimentally were then compared with those of class S4. Several mixes were prepared in order to determine the behaviour of concrete in the fresh state and in the hardened state.

The different mixes used in this study are summarised in Table 4.

Table 4. Mix proportion

	G 15/25 (kg)		G 8/15 (kg)		G 3/8 (kg)		C (kg)	Sand (kg)		SP (%)	W (kg)
	N. G	R. G	N. G	R. G	N. G	R. G		N. S	R. S		
O.C	6.43	-	7.62	-	5.26	-		9.92	-		
C.R1	5.47	0.97	6.48	1.14	4.47	0.79		9.92	-		
C.R2	4.50	1.93	5.33	2.29	3.68	1.58		9.92	-		
C.R3	3.22	3.22	3.81	3.81	2.63	2.63	5.03	9.92	-	1	2.52
C.R4	1.29	5.15	1.52	6.10	1.05	4.21		9.92	-		
C.R5	6.43	-	7.62	-	5.26	-		7.44	2.48		
C.R6	6.43	-	7.62	-	5.26	-		4.96	4.96		

2.6. Sclerometer test

The sclerometer test, according to Standard NF EN 12504-2, involves projecting a mass onto the concrete surface with a constant initial energy. Following the impact, part of the energy is absorbed by the concrete, while the other part causes the rebound of the mass. The impact energy is produced by a system of springs.

Furthermore, measuring the impact hardness enables the evaluation of the compressive strength of concrete in a non-destructive manner. This method is interesting because it is relatively simple to perform; it also allows for a quick check of the quality and regularity of concrete in a construction structure.

The determination of hardness is based on measuring the recoil undergone by a mobile device (controlled by a spring) following a collision between the device and the concrete surface. Note that this is one of the oldest non-destructive tests.

The test result is expressed by measuring the rebound distance of the rod. To assess the surface hardness homogeneity of a concrete facing and to identify areas with degradation or different mechanical characteristics, it is essential to exclude areas containing stone nests, crumbling, rough texture, or high porosity.

In 1984, T. Akashi and S. Amasak [40] stated that despite its apparent simplicity, the sclerometer test involves some complex problems related to impact and wave propagation.

2.7. Ultrasonic speed test

The ultrasonic speed test is employed to assess the homogeneity, uniformity, and detection of flaws such as cracks, voids, or discontinuities in the concrete, as well as the quality and integrity of concrete structures. The concept revolves around timing how long it takes an ultrasonic pulse to traverse a predetermined section of concrete. The velocity of the ultrasonic pulse within the material can be calculated using this time measurement and the distance between the transducers.

2.8. Compressive strength test

To assess compressive strength is a fundamental mechanical property of materials, measuring their ability to resist an axial compressive force. To evaluate the compressive strength of pavement samples, standardized tests are conducted, typically following ASTM or EN standards. These tests entail applying a progressive load to a sample until it reaches a breaking point, thereby determining the material's maximum compressive strength.

3. Results

The results of this research provide crucial information to guide road construction and maintenance decisions. They enable the determination of the feasibility and effectiveness of recycling aggregates, as well as their ability to meet the quality and sustainability requirements of road infrastructure. Additionally, they highlight the potential environmental benefits of recycling compared to the extraction of virgin materials, thereby promoting more sustainable resource management. These findings are also essential for developing standards and technical regulations to govern the use of recycled materials, as well as guiding political decisions and industrial practices in sustainable construction. The results of the destructive and non-destructive experimental programme are summarised in Table 5.

Table 5. Results of the destructive and non-destructive tests on different types of concrete

		OC	CR1	CR2	CR3	CR4	CR5	CR6
Density		2.30	2.35	2.21	2.35	2.27	2.37	2.36
Slump (cm)		11	9	13.5	11	10	12	12.5
Rebound Index	21 days	31.4	35.2	29.7	33.1	32.6	29.8	26.7
	28 days	34	38	30.2	36	35	33.5	30.4
Ultrasonic Pulse Velocity (m/s)	7 days	4 573	4 658	4 213	4 587	4 213	4 155	4 348
	21 days	4 839	4 630	4 323	4 642	4 310	4 225	4 478
	28 days	4 860	4 747	4 425	4 728	4 360	4 644	4 491
Resistance (MPa)	7days	28.21	32.07	28.45	33.64	23.51	23.42	24.91
	21days	37.06	41.84	31.74	42.157	31.48	27.55	28.57
	28days	40.32	44.661	35.17	42.824	41.19	31.71	30.51

3.1. Absorption kinetics

Figures 4, 5, and 6 depict the water absorption by immersion of various aggregates in the laboratory, irrespective of the nature of the granulometric skeleton. It is important to note that the diameter of the largest aggregate was standardized at 25 mm.

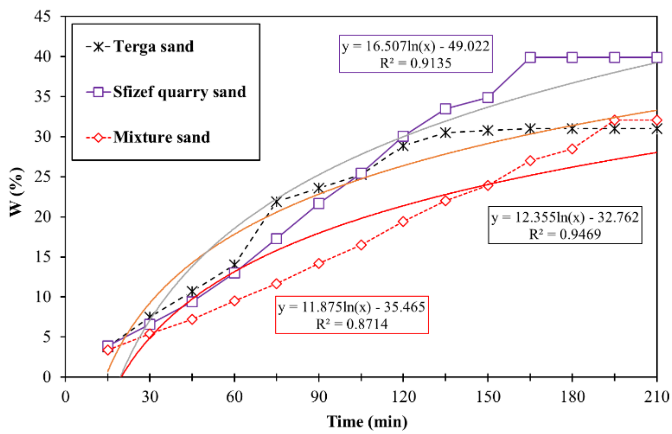

Fig. 4. Absorption kinetics of different sands (W%) as a function of time

The graph obtained for sands allowed the deduction of the following relationship: $y = 16.507\ln(x) - 4.3209$, where $R^2 = 0.99$ is the correlation coefficient.

This confirms that the SF sand has a much higher absorption coefficient than the other series of aggregates, likely due to the angular shape of these aggregates. Consequently, workability and, therefore, consistency will be lower. Additionally, the effect of the cement amount on the delayed mechanical behaviour of this material after immersion in water and on aggregates of unknown origin was quantitatively assessed.

Utilizing these recycled aggregates facilitated the development of the formulations depicted in Figs 4, 5, and 6. Consequently, the newly manufactured concretes in the laboratory need to be quantified with varying amounts of cement and different granular matrices. The types of these concretes would depend on the type and content of sand, as well as the type and content of gravel, which may be either natural or recycled. The existing relationship corresponds to the data obtained on the granular skeleton of concretes made with construction waste.

It is important to note that the recycled aggregates used exhibit high water absorption and porosity, and these are not instantaneous. Therefore, it is imperative to consider these two parameters in order to properly examine their absorption kinetics.

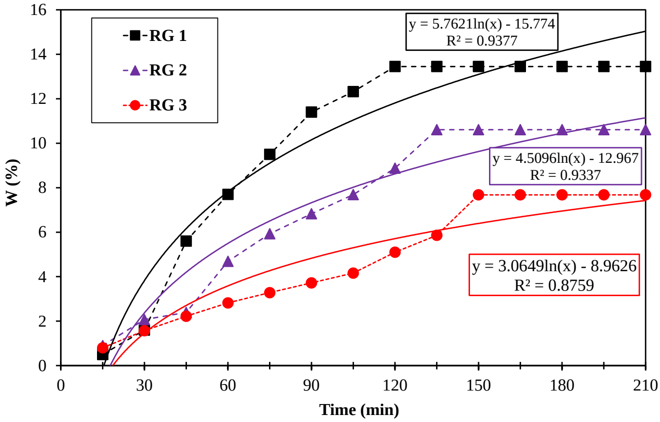

Fig 5. Absorption kinetics of recycled gravel (W%) as a function of time

According to the results obtained from the absorption kinetics, and based on the data cited above, it is evident that the water absorption of recycled aggregates is greater than that of natural aggregates. Furthermore, aggregates of class 3/8 exhibit higher absorption than natural aggregates of classes 8/15 and 15/25. It can therefore be deduced that the higher the percentage of recycled aggregates, the greater the water absorption and the larger the quantity of aggregates incorporated into the concrete mixture. According to Bodet [36], recycled crushed concrete aggregates exhibit higher water absorption, lower density, and lower homogeneity compared to natural aggregates. Regarding Ho [41], he found that crushed gravel (CG) has a density of 1.2, which is significantly lower than that of natural aggregates (sand) with a density of 2.67 and a negligible water absorption coefficient.

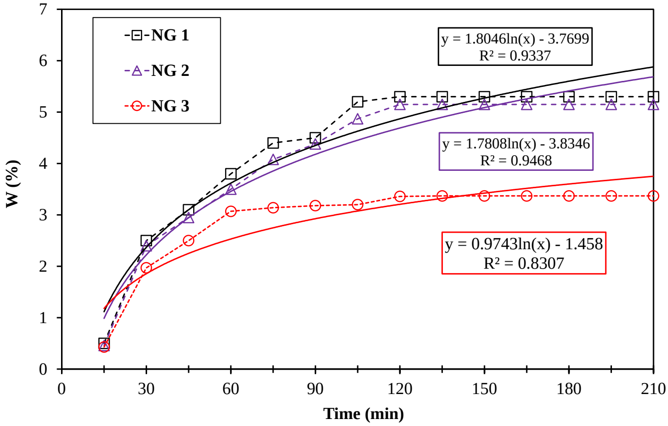

Fig. 6. Absorption kinetics of natural gravel (W%) as a function of time

Furthermore, the actual density of recycled aggregates is lower, and their water absorption is much higher than that of alluvial aggregates [19]. It should also be noted that aggregates from crushed concrete waste are considered non-standard and are suspected of having adverse effects on the durability of concrete [42].

The absorption kinetics tests conducted on sands and gravels all exhibited strong correlations, as evidenced by the high correlation coefficients (R^2) presented in Table 6. Excessive water absorption can detrimentally impact concrete properties, including strength, durability, and cohesion. Moreover, an excessive amount of water can elevate the water-cement ratio, thereby diminishing the concrete's strength.

When preparing concrete or other construction mixes, finer sand may necessitate more water to achieve the same consistency as coarser sand due to its higher water absorption capacity. Finer sand has a larger specific surface area, providing more potential sites for water absorption. Consequently, it may absorb more water per unit volume compared to coarser sand, due to the increased contact areas between the sand and water.

The use of finer sand may also lead to segregation and compaction issues in the concrete mix due to its fine texture, thereby affecting the mixture's stability. Adjustments in the proportions of water and cement may be necessary when incorporating finer sand to maintain the desired properties of the concrete. Laboratory testing can aid in determining the optimal amount of water required to achieve the desired mix consistency and in evaluating the overall impact of using finer sand on the final material's properties.

It is important to recognize that the specific surface area can vary depending on particle size, shape, and composition. The specific surface area values of fines and sand can influence the water requirements for a mix, cement hydration, and other properties of the final material. Therefore, it's crucial to identify and adjust properties such as consistency and compressive strength to ensure that adjustments lead to the desired outcomes.

The information in Table 6 indicates a good correlation of the results, thus confirming that the compositions of the recycled concrete exhibit strong consistency between the variables. This alternative approach can address various recycling challenges, including the composition of these aggregates, whether they originate from waste with normative composition or from poorly composed concrete results. By subjecting the different materials to absorption tests, it becomes possible to determine the optimal factor for establishing the water-to-cement (W/C) ratio, unaffected by the adsorption of materials, whether of natural or recycled origin.

Table 6. Correlations between water absorption and time

Material		Relationship	Correlation coefficient
NG	3/8	W=1.8046Ln(t)-3.7699	R^2= 0.9337
	8/15	W=1.7808Ln(t)-3.8356	R^2=0.9468
	15/25	W=0.9743Ln(t)-1.458	R^2=0.8307
RG	3/8	W=5.7621Ln(t)-15.774	R^2=0.9377
	8/15	W=4.5096Ln(t)-12.967	R^2=0.9337
	15/25	W=3.0649Ln(t)-8.9626	R^2=0.8759
Sand	ST	W=12.355Ln(t)-32.762	R^2=0.9469
	SS	W=16.507Ln(t)-49.022	R^2=0.9135
	MS	W=11.875Ln(t)-35.465	R^2=0.8714

TS: terga sand, SS: Sfisef quarry sand, MS: Mixture sand
NG: Natural Gravel, RG: Recycled gravel, W: Water absorption (%), t: time (s)

The term "powdery state of sand" refers to a fine and powdery texture, typically resulting from fragmentation or reduction into fine particles. In the context of sand used in concrete or other construction applications, powdery sand may possess a higher specific surface area compared to coarser sand. Specific surface area denotes the total amount of surface area exposed per unit volume or mass of a material.

The impact of the high specific surface area of powdery sand on water absorption can be significant. The values obtained also suggest that while the absorption rate for the 3/8 granular fraction is identical, there appears to be a divergence in the absorption rates of other granular fractions. This difference can be attributed to the composition of the waste material.

These results lend credence to the theory that the absorption rate provides a better explanation of the convergence possibly due to their origin and the reduction of the absorption surface for the recycled aggregates. Conversely, for the sands, these correlation factors allow us to underscore and consolidate our relative conclusions in the values obtained on the aggregates, suggesting that the envelope surrounding the gravel will have an impact on the absorption and possibly affect the physico-mechanical behaviour of concrete.

3.2. Concrete in the fresh state

It is important to understand the properties of concrete in its fresh state before it sets and hardens. Consistency and workability are among the most critical properties of concrete. Concrete slump is measured according to the recommendations of Standard NF P18-451 for all concrete mixes to be prepared. The results obtained are summarized in the following table.

Figure 7 illustrates the slump of recycled concrete, which includes 50% gravel. We observe a rate that is lower by 33.33% compared to the series of concretes containing 80% gravel. Conversely, the concrete containing 100% natural gravel shows greater water absorption since the recycled materials were introduced into water, inducing greater absorption for natural aggregates, as previously confirmed by De Larrard [43, 44].

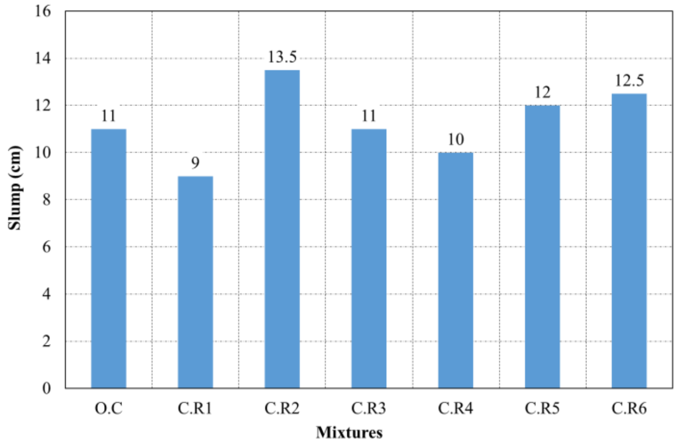

Fig. 7. Slump of different concretes

Furthermore, it has been revealed that excess water in concrete can lead to detrimental side effects on the quality of the concrete. This can be explained by the fact that dry aggregates absorb less water than those from construction waste, as the absorption of natural aggregates occurs immediately when water is added during the mixing process. Conversely, recycled aggregates exhibit higher water absorption due to their composition. These materials are coated with a layer of cement paste to prevent water absorption until the saturation threshold is reached.

It is known that larger diameter particles (2 mm) can make the mortar less workable, meaning it could be more difficult to handle and spread. Larger particles can create spaces between them, which can complicate the compaction of the mortar and achieving a smooth surface, and may have a lower specific surface area per unit volume, potentially reducing their water absorption capacity compared to finer particles.

However, these larger particles could also increase the void spaces in the mix, potentially raising the total water absorption capacity of the mortar. Additionally, these larger diameter particles (2mm) can make the mortar less workable, making it more difficult to handle and spread. The larger particles create spaces between them, causing difficulty in compacting the mortar and achieving a smooth surface. Larger diameter rubble may have a lower specific surface area per unit volume, which could reduce its water absorption capacity compared to finer particles.

However, these larger particles could also increase the void spaces in the mix, potentially increasing the total water absorption capacity of the mortar.

Based on the aforementioned findings, it can be said that a higher water-to-cement (W/C) ratio is required. This is confirmed by the need for excess water for hydration and by the low compressive strength of the manufactured concrete. According to Hansen and Narud [27, 45], recycled concrete aggregates continue to absorb water even after mixing. Therefore, the poor quality of our recycled concrete is not only linked to the quantity of mixing water but can also be attributed to the low strength of the recycled aggregates and the quality of the interface zones [23, 46].

3.3. Density of concrete in the hardened state

Density measurements were performed before conducting the mechanical tests on the hardened concrete. The results obtained are presented in Table 5.

Figure 8 provides information on the relationship between the slump of different concretes and their dry density. From all the results obtained, it is possible to verify that the behaviour is derived from the functionality of the composition of the concretes, the major influencing factor being the water-to-cement (W/C) ratio.

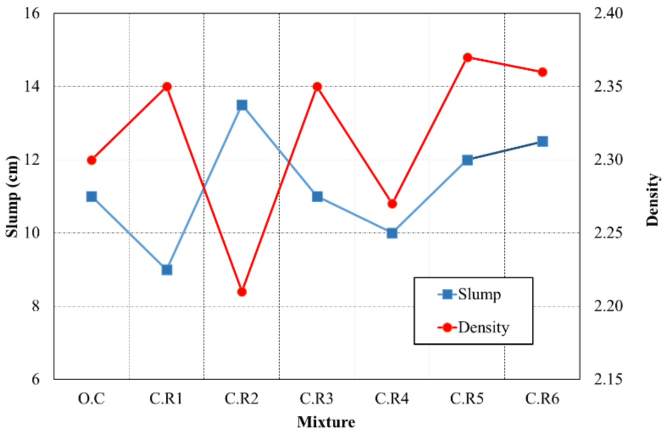

Fig. 8. Impact of slump on the density of different concretes

Different factors influence the consistency of various series of dry concrete, particularly dependent on the quantities of sand and gravel used. According to Bravo et al. [47], losses in concrete strength are mainly due to certain factors. It has been found that the weaker the mechanical strength provided by the recycled aggregate, the greater the water absorption by the recycled aggregate.

An increase in the number of fragile zones in the concrete, i.e., the interfacial transition zones between the old cement paste and the natural aggregate, as well as between the recycled aggregate and the new cement paste, is observed. Additionally, Bravo et al. [47] discovered that the size, composition, and origin of the recycled aggregate significantly influence the results for this type of material [34].

The manufacturing of recycled concrete in this investigation presented satisfactory results, which perhaps allows for the reuse of these elements from waste. The ratio was quantified according to the material needs, thus addressing the requirements that had to be anticipated for recycled concrete without considering a scale used to balance the deficiencies induced by these mixtures. Furthermore, it is important to note that the density of the mixtures depends, on the one hand, on the relative proportion of their various constituents and, on the other hand, on the granular compactness of the mixture, which depends on the granulometry of their different constituents [48].

3.4. Non-destructive determination of concrete strength (Sclerometer & Ultrasound)

It is widely acknowledged that non-destructive testing is crucial for controlling the quality of construction materials and indirectly measuring characteristics such as compressive strength, homogeneity, porosity, and durability of concrete.

The results of this test, based on an average of 12 readings on cubic test pieces, are reported in Table 5.

Figure 9 illustrates the evolution of the rebound index of different concretes at ages 21 and 28 days, while Figure 10 shows the evolution of ultrasonic speed over time.

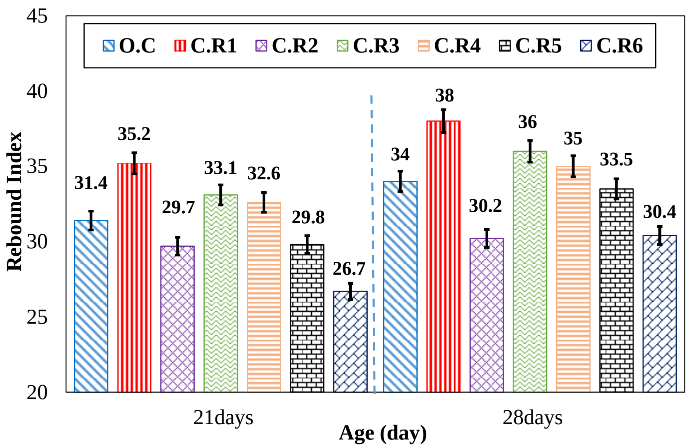

Fig. 9. Evolution of the rebound index of different concretes as a function of age

The results clearly indicate that high cohesion between the grains leads to a better constitution of the granular skeleton and rapid wave propagation, which can testify to the quality of the concrete under consideration. The constituents of concrete are expected to induce good adhesion in this heterogeneous medium. In this case, the recommendations for the preparation of this type of concrete must be strictly adhered to.

Furthermore, it was revealed that recycled aggregates have a higher water absorption due to the composition of waste concrete, which is coated with a layer of cement paste that prevents the absorption of the necessary water until the saturation threshold is reached.

This results in a higher actual water-to-cement (W/C) ratio, which leads to strengths converging towards those of concretes made with recycled aggregates due to the saturation of the granular skeleton upstream.

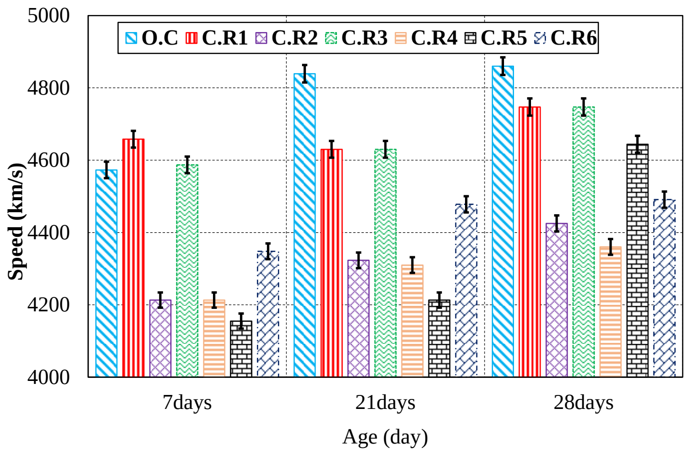

Fig. 10. Evolution of ultrasonic pulse velocity over time for different concretes

Better cohesion between the grains leads to a superior constitution of the granular skeleton and faster wave propagation, thereby testifying to the quality of the manufactured concrete. Constituents such as sand contribute fines that enhance adhesion, resulting in improved plasticity of the concrete. However, certain factors, such as the water-to-cement (W/C) ratio, must be considered upstream to prevent concrete degradation. It is also crucial to take into account certain requirements, like the maximum level of fines in the mixture and, possibly, the amounts of additives for this type of material. According to Moniz et al. [48], the granular materials used in the sub-base must contain a significant quantity of angular-shaped aggregates, typically produced by crushing, to generate high frictional forces between these aggregates.

3.5. Compressive strength

Figure 11 illustrates the evolution of compressive strength with the age of the concretes tested. The results indicate that replacing quarry gravel with recycled aggregates enhances the compressive strength of the concrete. The preparation of concrete with more than 15% and up to 50% recycled gravel led to an increase in compressive strength between 7 and 28 days. However, a slight decrease was observed at a 30% substitution level because the concrete mixture absorbed water during mixing, negatively impacting the compressive strength. Conversely, concrete incorporating 80% recycled aggregates exhibited satisfactory mechanical characteristics, with a slight strength reduction likely due to the significant water absorption of the aggregates.

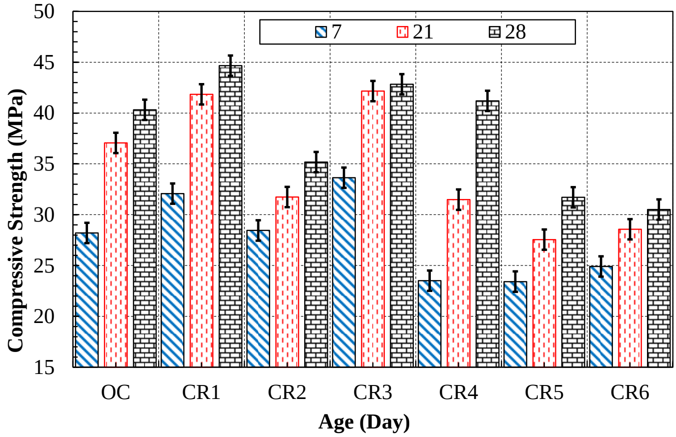

Fig. 11. Evolution of compressive strength

It is worth noting that further explanations can be offered for these findings. Indeed, since dry natural aggregates absorb less water than those derived from construction waste, the absorption of water by natural aggregates occurs as soon as water is introduced during the mixing of concrete. Additionally, Fig. 11 shows an improvement in the compressive strength in the CR1 concrete series. This result was corroborated by Evangelista et al. (2007), who analyzed the compressive strength of different concrete mixes containing fine recycled aggregates and found values comparable to those of reference concrete.

Moreover, these positive results could be justified by the presence of non-hydrated cement particles in the recycled fine aggregate and also by the good adhesion between the cement paste and the fine particles of the recycled aggregates, which exhibit high porosity. Similar findings were also reported by Gomes et al. and Etxeberria et al. [16, 34]. Furthermore, according to researcher Bilodeau [49, 50], intergranular friction inhibits the movement of particles and increases the angle of internal friction of the material, thereby enhancing its resistance to shear.

Finally, regarding concretes incorporating recycled sand of the same composition, a significant drop in compressive strength was observed, indicating the optimal quantity of local sand to be used.

4. Conclusions

Based on the results obtained, the primary conclusions can be summarized as follows:

The results of this study indicate that the substitution rate of demolition and construction waste in concrete production can reach up to nearly 80%. This underscores the significant potential of recycled aggregates in reducing dependence on natural resources and promoting sustainable practices in the construction industry. By substituting such a high proportion of materials derived from construction waste, it is possible to decrease the environmental footprint of concrete production while minimizing the amount of waste sent to landfills. This also demonstrates the economic and environmental viability of using recycled aggregates in construction, contributing to the promotion of a circular economy and the achievement of long-term sustainability goals.

The tests carried out at 28 days revealed that the porosity of concrete is impacted more by the volume of paste (cement + water + trapped air) than by the porosity of the granular skeleton. The porosity increases with the replacement level of natural aggregates with recycled aggregates.

The difference in water absorption between natural and recycled aggregates plays a crucial role in the concrete mixing process. While natural aggregates begin to absorb water as soon as they are introduced into the mix, aggregates from construction waste have a lower initial water absorption. This distinction highlights the importance of water management when formulating concrete mixtures, particularly when using recycled aggregates. These differences in water absorption must be taken into account to ensure the quality and durability of the concrete produced.

Both non-destructive and destructive tests clearly showed that our results converge towards the same values, indicating that the results obtained were well confirmed by the methods adopted in this research.

Future research on aggregate recycling should focus on developing advanced recycling technologies and optimizing construction practices for the integration of recycled materials. An evaluation of environmental and economic impacts can also be studied. These efforts aim to promote sustainability in construction and advance aggregate recycling in the civil engineering field.

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