THE USE OF RECYCLED CONCRETE POWDER AS SUPPLEMENTARY CEMENTITIOUS MATERIALS FOR MANUFACTURING CONCRETE

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Resume

Construction development is inevitable, while despite its advantages and its benefits, it may lead to several problems related to landfill and its storage, referring to the high volumes of concrete waste currently generated annually, almost 2.0 ton/per capita according to Eurostat. In Algeria, the government has integrated waste management strategy [3] provision to recovering 60% of construction waste by 2035, which can translate to an urgent need to find innovative ways to recycle concrete waste. One is using those wastes to produce aggregates; however, around 20% of those aggregates represent fines, wich can lead to several issues if not considered in the concrete mixture. This work is an investigation that allows for using this fine fraction as partial replacement of cement. The result confirms the feasibility of using this material efficiently by applying an optimization process, ensuring an optimal cement replacement percentage.

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1 Introduction

Many construction works are being implemented and many projects will be born in the future to serve the development of Algeria's infrastructure, and one of the effective strategies around the world is the sustainability development that became an obligation [1]. The concept is to try to find possibilities for recycling and reusing those waste to thereby drive the institution of a circular economy [2], Algeria is also imposing itself by raising and integrate the waste management strategy, it is expecting to recovery more than 60% of construction waste in 2035 [3]. The construction sector is responsible for 25% of the total CO_2 emissions [4], whereas only the cement production is responsible for about 8% of those emissions. This is among the reasons that pushed Algerian government to enter many agreements, among them the treaty with the Federal Ministry of Germany and the European Union, for the German Society for International Cooperation "GIZ" program, which is an ambitious program to contribute to the reduction of greenhouse gas emissions targeting at least 7% by 2030. This program includes several points, among them the protection of the environment and biodiversity of the Algerian coast and sustainably strengthen value chains in waste management. In addition, create a waste collection and recycling system and also develop and introduce new offers of qualifications and specific training for the waste sector [5]; it also puts several strategies such as National Strategy for Integrated Waste Management by 2035 (SNGID-2035). In addition the realization of eight technical land-fill centres for inert waste across the national territory will allow rational management of this waste and recovery in construction, as well as the National Strategy and Action Plan for Biodiversity 2016 - 2030, the National Action Plan on sustainable consumption and production patterns by 2030 (PNA-MCPD) [6].

In Algeria, millions of tons of waste are generated every year from the construction sector, according to the

***Figure 1** The concrete recycling procedure until obtaining the fine fraction*

report of National Waste Agency in 2020 about the state of waste management. The quantity of construction and demolition waste produced in 2020 is estimated at 13 million tones and it increases every year, the estimate of this inert waste that comes from the construction and demolition sector will be around 27 million tons in 2035 [3]. Hence, the urgent need to adapt to the sustainable development approach by finding effective techniques for managing waste and, above all, reusing it in various applications.

Recent researches tend to find new ways of recovering waste to fully fulfil their obligations; they proceed to the valorisation of this waste generated by construction sector, either in the form of aggregates for reuse instead of natural aggregates [7-11]. In addition, in the manufacture of fines and valued as new materials that can be used as a partial replacement for cement [12]. Moreover, that is what we were investigating in this research, because this practice is often limited due to the side effects often related to their very high water absorption and especially when we use the coarser aggregate. Therefore, this investigation is one of those solutions that could be very beneficial, about the feasibility of using finely ground concrete from waste concrete as a component of concrete. Instead of using fine recycled concrete as aggregates, we propose to use them as mineral addition (supplementary cementing material SCM). After the usual recycled concrete aggregate manufacturing process, in which the concrete was broken in small pieces, and crushed, we proceed to an additional process of crushing and sieving until obtaining a powder with maximal diameter lower than 80 µm. In the following, this powder can be used as a substitute for usual addition, such as limestone filler, silica fume, or blast furnace slag or even fly ash, what would reduce quarrying of natural resources.

Nevertheless, the use of recycled aggregate fines in the manufacture SCM is now a research and development path as an addition to clinker.

The objective of this study was to evaluate the possibility for use of those fines in manufacturing mortar, the appropriate replacement percentage by evaluating the performance of a common concrete composed using them, and to assess that we started by reporting a physical and chemical characterization investigation on those recycled concrete fines. Then, the evaluation of its influence on the mechanical resistances to be able to draw approaches and recommendations for an optimal use of those fines.

In view of results from this work, it is therefore possible to use the powder from the fines recycled concrete in the raw to be used as a mineral addition in cementitious materials, by incorporating them into mortar and subsequently into concrete.

***Figure 2** The manufacturing process of recycled concrete powder in the laboratory*

***Table 1** Results of chemical analysis of recycled concrete powder*

Sample of Recycled Concrete Powder	Component (%)
Calcimeter Tests $CaCO_3$	48.80
Chlorine Test (Cl^-)	0.25
Sulphate Test	≥ 0.01
The insoluble matters	50.95

2 Materials and methods

2.1 Materials preparation

The recycling process that has been adopted in this work-study for the manufacturing process to obtain recycled aggregate, more precisely, the fine fraction (recycled concrete powder) that was used in those experiments, is shown in Figure 1.

The research has been carried out using the raw materials from concrete waste; the concrete has been recovered for test specimens, which come from several construction sites located in the region of Bechar-ALGERIA. The recycled concrete powder manufacturing process started by crushing, and screening, then passed to the grinding using a micro-grinder and then sieving at 80 µm. Figure 2 illustrates the laboratory material employed and schematization of the manufacturing process.

2.2 Characterization of fines from concrete recycling

2.2.1 Chemical characterization:

For a better understanding of the nature of those fines (recycled concrete powder) a basic chemical characterization tests were carried out on this material for identifying minerals, the results are shown in Table 1.

Chemical identification tests revealed that:

- Calcimeter Tests using Bernard Calcimeter: about half of those fines is limestone, which make sense given the calcareous nature of the gravels in this region.
- Chlorine Test: revealed that the amount of chlorine does not exceed 0.25%.
- Sulphate Test: we detected only traces (less than 0.01), which is largely far from the limit, which is 0.80%. The rest of the material constitutes of minerals insoluble, which represent around half of the materials.

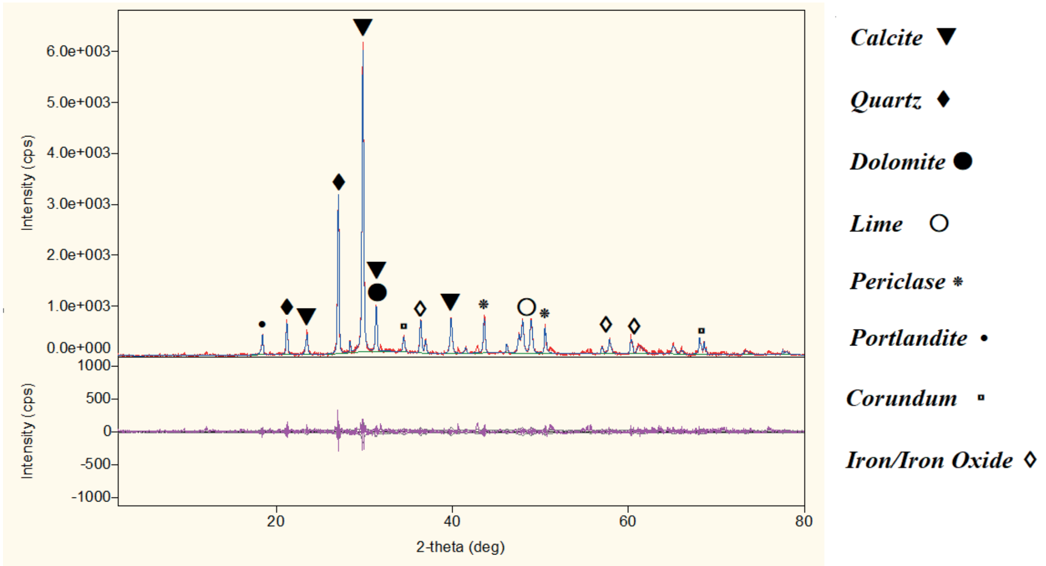
Those analyses conducted lead to the conclusion that recycled concrete powder is compatible for introduction into cementitious matrices. Additionally, even if there exists a potential variation in the chemical composition between different concrete waste sources, that is attributed to the components, nature, and origins of recycled concrete and its aggregates. According to the literature, recycled concrete may often contain high percentages of calcite or limestone, with quartz being the most common, together with small amounts of lime, portlandite, and some iron oxides [12-14].

Acknowledging to these potential variation, preliminary assessments indicate that those fluctuations do not significantly compromise the properties of the concrete, although this aspect requires validation in future researches.

To better quantify and comprehend the extent of these variations, further analyses based on XRD have been conducted.

2.2.2 Physical characterization

We determined the apparent density of Recycled Concrete Powder according to standard EN 196-6 [15], to compare it to that of the additions and that of the binders.



Phase	Formula	Content (%)
Calcite	$CaCO_3$	56.04
Quartz	SiO_2	19.59
Dolomite	$CaMg(CO_3)_2$	9.17
Lime (Calcium oxide)	CaO	5.51
Periclase (Magnesium oxide)	MgO	4.02
Portlandite (Calcium hydroxide)	CaH_2O_2	2.16
Corundum (Aluminum)	Al_2O_3	2.13
Iron/iron oxide	Fe/ Fe_2O_3/FeO	1.38

Figure 3 *The results of XRD analysis of recycled concrete powder*

The density of Recycled Concrete Powder is 650 kg/m³, which is comparable to that of other additions, such as silica fume (400 to 650 kg/m³), and limestone fillers (500 to 700 kg/m³).

2.2.3 XRD characterization

To better understand the recycled concrete powder, we have proceeded to the X-ray diffraction "XRD" tests, which has been made with the following operating parameters: Cu Kα radiation, 45 kV, 200 mA power generator. An angular range of 5-70° 2θ was measured with a scan speed of 5° per minute, the results are presented in Figure 3.

The XRD analysis reveals that these fines are mainly composed of calcite and quartz, which makes sense when we relate it to the nature of the aggregates in the region of Bechar, Algeria; small amounts of lime, portlandite, and some iron oxides were observed, as well.

Other researchers as Oksri-Nelfia et al noted that they had found that the recycled concrete fine containing 73% of $CaCO_3$, as well as around 2.4% of portlandite [12]. Liu et al. found that the recycled concrete powder contain 52.53% of CaO, 27.87% of SiO_2, 7.04% of Al_2O_3, 4.9% of Fe_2O_3, 3.53% of MgO, 1.27% of K_2O, and finally 0.05% of SO_3 [16]. Cantero et al., mention, in their review about construction and demolition, waste powder that can contain between 36% and 70% of SiO_2, 6% to 19% of Al_2O_3, 3% to 6% Fe_2O_3, as well as less than 20% of CaO, along with traces of other oxides; it may prove to be a suitable Supplementary Cementitious Material [17].

Although the results found are in accordance with the literature, however, the chemical components can vary, and there is sometimes a difference in the proportions of materials. This variation is often due to the nature of the aggregates used, as aggregates typically make up 60 to 75% of the volume as fillers in concrete materials [18].

2.3 Materials used for mortar formulation

For the formulation of mortar in this case we used a cement which is CEM I 42.5 N-SR 3 from Lafarge-Algeria (MOUKAOUEM), and for the sand we used a quarry sand (0-3) from the region of Bechar-Algeria; these characteristics are given in Table 2.

Table 2 Characteristics of sand

Sand	Value	Description
Sand fineness	mf = 2.05 (1.8 ≤ mf ≤ 2.2)	sand mostly fine grain
Equivalent sand test	esp. = 85.6 (esp. ≥ 80)	very clean sand

Table 3 Composition of mix mortar

Replacement share (%)	0	5	10	15	20	25	30	35	40	45	50
Sand (g)	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350	1350
Water (ml)	225	225	225	225	225	225	225	225	225	225	225
Cement (g)	450	422.5	405.0	382.5	360.0	337.5	315.0	292.5	270.0	247.5	225.0
Recycle Concrete Powder (g)	0	22.5	45.0	67.5	90.0	112.5	135.0	157.5	180.0	202.5	225.0

Table 4 The effect of percentage of replacement share on mechanical strength in MPa

Mechanical strength (MPa) \ Replacement share (%)	0	5	10	15	20	25	30	35	40	45	50
Flexural strength (7 days)	5.5 (±0.5)	5.0 (±1.0)	5.0 (±1.0)	4.5 (±1.0)	4.5 (±0.5)	4.0 (±1.0)	4.0 (±1.0)	3.5 (±1.0)	3.0 (±1.0)	2.5 (±1.0)	2.0 (±1.0)
Flexural strength (28 day)	6.0 (±0.5)	6.0 (±0.5)	6.5 (±0.5)	6.0 (±1.0)	5.5 (±1.5)	5.5 (±0.5)	5.0 (±1.0)	5.0 (±0.5)	4.0 (±1.0)	4.0 (±0.5)	3.0 (±1.0)
Compressive strength (7 day)	22.5 (±2.0)	23.0 (±1.0)	23.0 (±2.0)	22.5 (±2.0)	22.0 (±2.0)	21.0 (±2.0)	20.0 (±1.0)	19.0 (±1.0)	16.0 (±1.0)	13.0 (±2.0)	10.0 (±2.0)
Compressive strength (28 day)	29.5 (±1.0)	29.5 (±1.5)	30.0 (±1.0)	29.0 (±1.5)	27.5 (±2.0)	26.5 (±1.5)	24.5 (±2.0)	22.0 (±2.0)	19.0 (±1.0)	17.0 (±2.0)	14.0 (±2.0)

2.3.1 Preparation of mortar

These materials were used to make a mortar (1/3) with a W/C = 0.5, according to the standard EN 196-1 [19], with different percentages of cement replacement by recycled concrete powder.

Procedure: Mix the standardized sand with the cement to be tested and the water in the following proportions: 450 ± 2 g of cement, 1350 ± 5 g of standardized sand and 225 ± 1 g of water.

The quantities for all the components are summarized in Table 3.

The mix is made homogeneous by using the equivalent binder by adding the recycled concrete powder, however, it has been noticed that the workability appears to decrease with the increase of the amount of fines on the recycled concrete, it started to be noticeable after reaching 40% of replacement. The mortar was filled into the molds using vibration, with adjustments made based on the mortar's workability ensuring an effective compaction of the specimens.

Once the mortar was ready, it was put into 40x40x160 mm prismatic molds. The installation was carried out by vibration. The samples were identified and stored in a container filled underwater, at a temperature of 25°C ± 1°C until the compressive and flexural strengths tests (7 and 28 days).

3 Results

The destructive tests, carried out on mortars after the curing period, consist of studying the tensile and compressive strengths of mortars, made without and with different replacement level of recycled concrete powder at 7 days and 28 days, according to the standards. For defining the resistance classes of mortars, to evaluate the contribution of additions to the mechanical performance of mortars, the specimens (six for each mixture) were drawn from the pans and tested in bending and compression.

3.1 Effect of replacement share on mechanical strength

The compressive, and flexural strengths of the mortar, as a function of the addition replacement percentage, are represented in Table 4 and Figure 4.

From the obtained results, it was observed that within the range of 0 to 15% cement replacement with

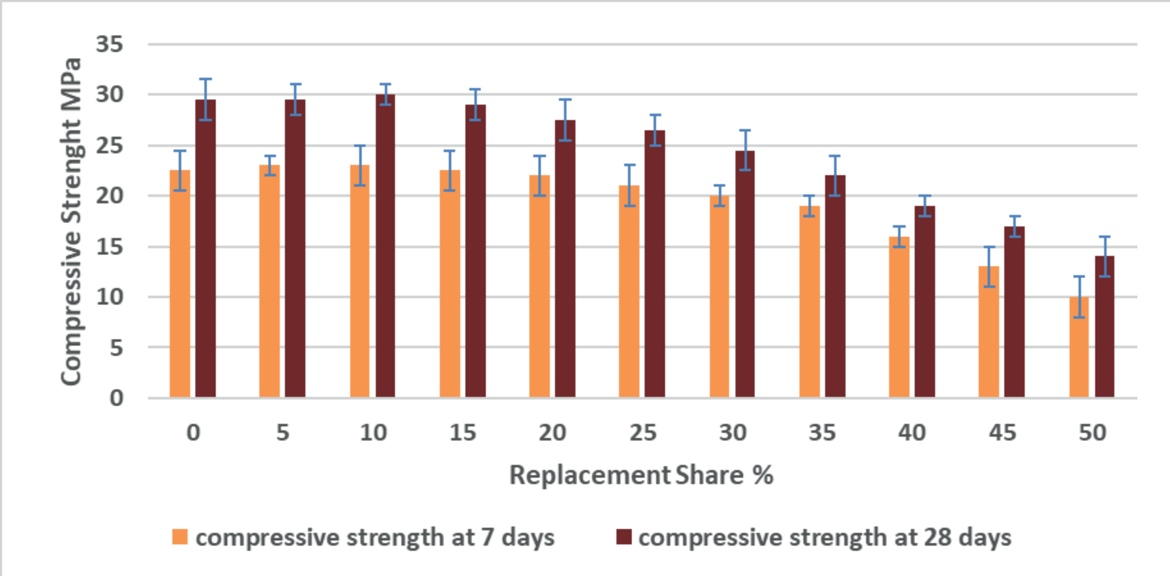


Figure 4 *The effect of replacement share on compressive strength in MPa*

Table 5 *Recycled concrete powder passing percentage depending on fineness size*

Size (µm)	Passing (%)
800	95
500	80
315	70
250	60
160	50
125	40
80	25

recycled concrete powder, the optimal point lies in this interval with very slight differences. It was also revealed that from an economic standpoint, it could achieve up to 20% or 25% replacement to at least maintain the normalized resistances.

3.2 Effect of finesse size on mechanical strength

It is noticed that the manufacture of fines at 80 µm is quite difficult, and consumes enormous amount of energy. That is why we tried to find the ideal fineness size of the recycled concrete powder by varying the fineness from 80 to 800 µm, to preserve a maximum of energy in the manufacture of fines, to be more profitable, however, the fineness of the fines could modify the properties of the mortars.

The recycled concrete powder in this experiments result using the output collected after crushing and grinding the same recycled concrete, the resulting material shown after sieving a grading presented in Table 5.

Then, the study was conducted about the effect of the fineness of the used recycled concrete powder on the mechanical resistance of the mortar. A mortar 1/3 with W/C = 0.5 with 20% replacement of cement by recycled concrete powder, was made with different fractions of the recycled powder: 0/80 µm, 0/125 µm, 0/160 µm, 0/250 µm, 0/315 µm, 0/500 µm, and 0/800 µm. Table 6 presents the results concerning the compressive strength at 7 and 28 days of mortar according to recycled concrete powder fineness. Additionally, Figure 5 provides a more elucidated illustration of the compressive strength results at 28 days for the mortar based on the fineness of the recycled concrete powder.

From results in Table 6 and Figure 5 it can be observed that, for a fineness up to 160 µm, the compressive strength remained consistent. It was slightly affected and decreased marginally in the range from 250 to 315 µm. On the other hand, it is worth noting that the strength becomes more affected with fineness variations exceeding 500 µm.

3.3 Evaluation of water absorption and the necessary correction

It has been noticed that the workability decreases greatly, especially at the high replacement shares, so it was decided to evaluate and quantify the water demand

Table 6 *The compressive strength of mortar according to recycled concrete powder fineness*

Strength (MPa) \ Powder size (µm)	80	125	160	250	315	500	800
compressive strength (7 days)	22.0 (± 2.0)	22.0 (± 2.0)	22.0 (± 2.0)	22.0 (± 1.5)	21.5 (± 2.0)	21.0 (± 2.0)	21.0 (± 1.0)
compressive strength (28 days)	27.5 (± 2.0)	27.5 (± 2.0)	27.5 (± 1.5)	27.0 (± 2.0)	27.0 (± 1.0)	26.5 (± 1.0)	25.0 (± 1.0)

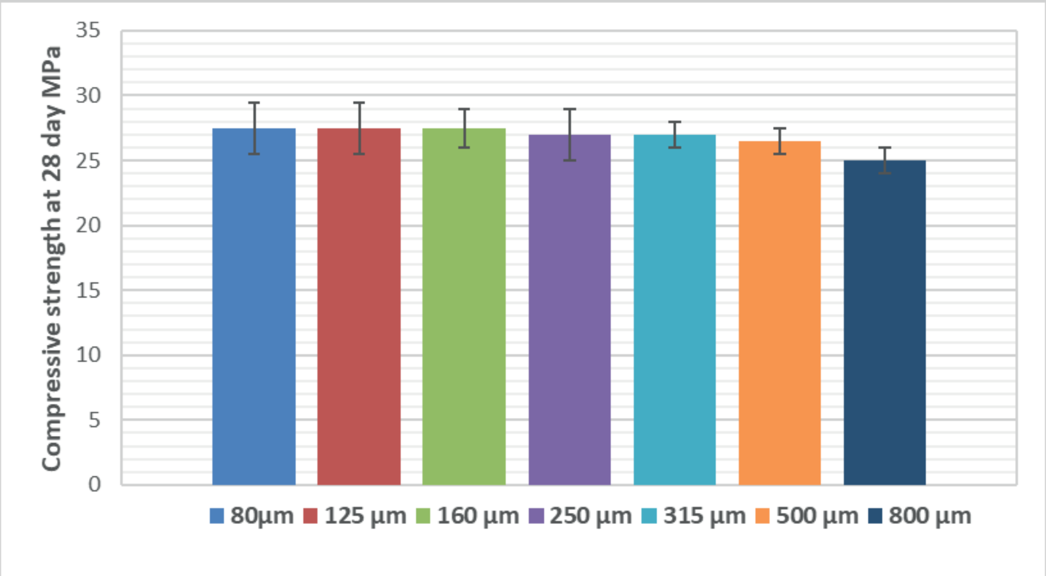


Figure 5 *The compressive strength of mortar according to recycled concrete powder fineness*

Table 7 *The effect of cement replacement by recycled concrete powder on water demand.*

Replacement share (%)	Water (%) over binder	Consistency value needle depth D (mm)
0	27	5
10	27	7
20	28	6
30	29	6
40	30	6
50	31	6

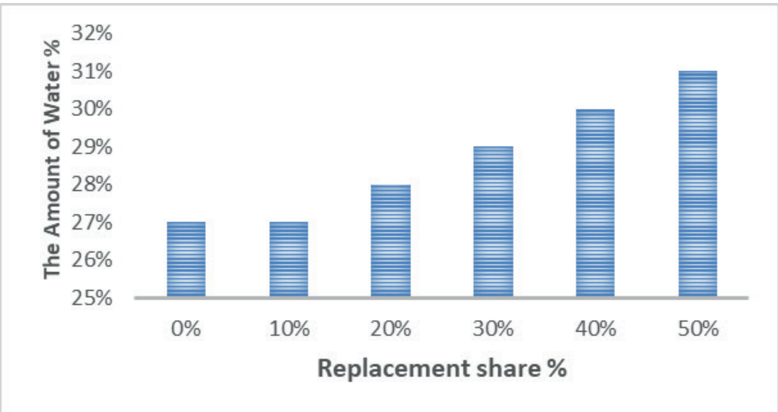


Figure 6 *The effect of replacement share on water demand*

__Table 8__ Concrete Mixture (kg/m^3)

Materials	Formulation A	formulation B
Cement	875	700
Recycled concrete powder	0	175
Sand 0/4	900	900
Gravel 3/8	730	730
Water	245	254
Super-plasticizer	26	21
Gravel/Sand	0.81	0.81
Super-plasticizer/Cement	0.03	0.03
Water/Binder	0.28	0.29
Cement/Binder	1.00	0.80

using the Vicat device, equipped with its consistency probe in accordance with the standard EN 196-3 [20], to evaluate the necessary correction for the amount of water. Table 7 and Figure 6 present the results of experiments about the effect of cement replacement by recycled concrete powder on water demand.

Indeed, the decrease in workability is depending on the percentage of recycled content. Beyond 20% replacement, it is necessary to make a water correction.

Based on observations, it appears that there is a need for approximately 1% of additional water for each 10% increase in cement replacement by recycled concrete powder.

Although the increasing replacement of cement by recycled concrete powder appears to causes a drying of the fresh mixture, in which it requires an addition of water for correction to maintain consistent workability, it is noteworthy, based on visual observations, that this adjustment does not affect the mixture's homogeneity, which remains intact and uniform.

3.4 Influence of recycled concrete powder on concrete

A concrete is manufactured based on previous formulations [21-24], so we applied an optimization based on the interpretations of the previous results, in this investigation. The goal was to achieve a concrete mix with satisfactory workability and exceptionally high strength, particularly in terms of compression resistance. This iterative process involved adjusting the key factors, such as the water-cement ratio, aggregate properties, and the use of additives. The aim was to develop a concrete mix that not only met, but also exceeded the performance expectations.

Table 8 presents the basic mixture (Formulation A) that was used it as a reference formulation, as well as the mixture with the integration of recycled concrete powder (Formulation B). In this formulation, 20% of cement "CEM I 42.5 N-SR 3" was replaced by the recycled concrete powder and some parameters were optimized as indicated. The sand used is a coarse sand (0-4), clean, with a very high limestone content, exceeding 95%. The gravel utilized is a 3-8 gravel with a mass loss of less than 20% in the Micro-Deval test [25]. These aggregates are recommended for use in the production of high-performance concrete; and finally, the super-plasticizer used is Sika® ViscoCrete®-4032 RMX. The concrete mixing process was carried out during 15 minutes in a horizontal manner, for ensuring an optimal mixing of the components.

Using the formulation provided in Table 8, has led to a successful production of fluid concrete, which appears stable and shows no initial signs of segregation.

3.4.1 Influence on the fresh state (spreading)

The workability of fresh concrete was tested using Abrams cone, the flow of each formulation was measured after 15 minutes of mixing. The results represent the average of three tests for each formulation. The founding are represented in Figure 7.

The observations indicate a slight reduction in the workability of the concrete, while it still maintains its ability to flow. This suggests that workability remains manageable, and the concrete retains its fluid properties when producing concrete with a 20% of cement replacement by recycled concrete powder.

A remarkable variation regarding the flow has been observed, which suggests that this concrete is likely responsive to specific factors, including mixing conditions, duration, and the moisture content of the aggregates.

3.4.2 Influence on the hardened state (compressive strength)

The evaluation of the compressive strength of concrete was conducted on cubic specimens with side

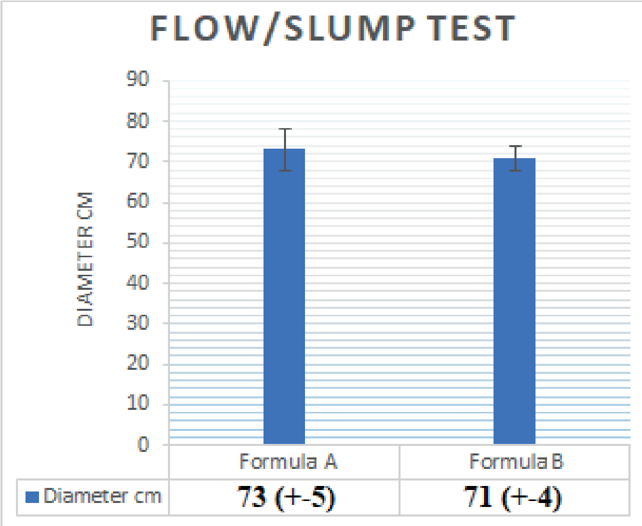


Figure 7 *The effect of recycled concrete powder on concrete flow.*

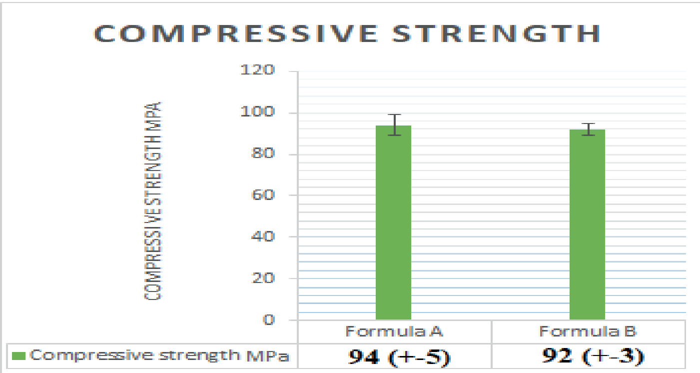


Figure 8 *The effect of recycled concrete powder on compressive strength of concrete at 28 day*

measuring 150 mm at 28 day of cure; the presented results in Figure 8 represent the average compressive strength of six specimens for each mixture, to quantify the effect of recycled concrete powder on compressive strength of concrete at 28 day.

It is noticeable that the compressive strength was not significantly affected, with only a minor variance of approximately 2 % observed, when incorporating the recycled concrete powder. The concrete has effectively maintained its robust compressive strength.

Furthermore, the examination revealed that the concrete exhibited a wholly brittle breakage mode, indicating that, in this formulation, the inclusion of fibers is necessary.

4 Conclusions

From the results obtained, it is possible to assess to what extent the recycle concrete powder is compatible with cementitious matrices, therefore, the following conclusions were drawn:

1. The mortars were prepared without and with ranging from 5 to 50 % of the cement replacement by recycled concrete powder; it has been found that, up to 10 %, replacement had no adverse effects and the concrete kept its properties well, and the effects are acceptable, sometimes rather negligible up to a 20 % of replacement share. However, beyond 25 % we observe a start of significant decrease of mechanical properties.
2. Other mortars were prepared with 20 % of cement substitution by recycled concrete powder, varying the fineness size of it; we found that for a fineness up to 160 µm, the compressive strength remained consistent. Then, it starts to become slightly affected and decreased marginally in the range from 250 to 315 µm. However, when the finesse exceed a 500 µm the strength becomes significantly affected.
3. For the water demand, it is necessary to make a water correction from 20 % replacement, and this correction must be around 1 % of the binder mixing water for each 10 % of additional replacement share.
4. After formulating a concrete mix by applying optimizations deduced from previous results, we were able to obtain fresh and hardened properties

using recycled concrete powder approximately similar to those of the reference concrete.

5. We conclude from these findings that in the formulation of concrete using the recycled concrete powder, the concrete can effectively maintain its key characteristics and essential properties, particularly in terms of workability and compressive strength. This is applicable even to high-performance concrete, as well.
6. From an economic stand point, replacing 20% of the cement quantity, which is notably expensive, by recycled concrete powder, obtained at a minimal cost during the manufacturing of recycled aggregates, proves to be highly advantageous. This approach can offer substantial economic benefits in addition to its environmental advantages.

Based on these conclusions, it can confidently be asserted that substituting a portion of the cement with recycled concrete powder can be done effectively, all while preserving the fundamental properties of the standard concrete. This sustainable practice not only reduces the demand for new cement but contributes to environmentally friendly construction methods, as well. The use of recycled materials in concrete production is an essential step towards achieving greater sustainability in the construction industry.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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