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Research Article

The effects of the quality of recycled aggregates on the mechanical properties of roller compacted concrete

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Abstract

This study investigates the performance of roller compacted concrete (RCC) made with recycled aggregates derived from crushed demolished concrete with various proportions of natural. The experimental study examines substituting various proportions of natural aggregate (3/8, 8/15, and 15/20) with recycled aggregate. The replacement rates range from 0% to 100% in increments of 25%. Eleven different mixtures have been made by changing the amount of recycled aggregate used, with and without pre-wetting, before being added to concrete. Additionally, 5% of the cement content was substituted with silica fume and slag in each composition. An experiment test was done to see how recycled aggregate-based BCRs' performance changed with the incorporation rate on fresh and hardened concrete's mechanical and physical properties. Physical parameters, including volume masse, vebe time consistency, and mechanical properties such as compression resistance, flexion resistance, and ultrasonic pulse speed, were measured over time. The results found were compared to the control mix made with 100% natural aggregates. Those results show that as the replacement rate increases, the water absorption rate increases with a decrease in mechanical strength. In addition, the pre-wetting treatment did not significantly impact mechanical strength. This can be explained by the characteristics of the recycled aggregate, such as high absorption, low resistance to wear, and low density, which were caused by the residual paste adhered to the recycled aggregate.

1.Introduction

Protecting the environment is absolutely essential to human being. Modern construction standards with several considerations, including environmental awareness, protection of natural resources, and sustainable development. Hence, it is crucial to minimize the use of natural resources and implement effective strategies to manage and recover solid waste. Today, concrete is the most widely used as construction material in the world, 4 to 10 times more than metals and 10 to 30 times more than cardboard or plastic[1] Moreover, aggregates represent the majority of the volume of concrete [2]; As a result, there is a huge demand for aggregates in the construction field. To meet this demand, it is essential to limit the use of natural aggregates and maximize the use of recycled aggregates. The increasing use of natural coarse aggregates is causing ecological disruption. Therefore, the utilization of alternative resources in the construction industry is imperative. Numerous studies have shown a keen interest in this field, whereby environmental preservation has emerged as a significant target, specifically regarding the use of recycled concrete aggregates (RCA) [2].

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According to the literature, the European Union and the United States of America produced 850 million tons and 530 of deconstruction waste in 2014, respectively [3]. In comparison, the amount of deconstruction waste generated in 2015 reached a staggering 1.5 billion tons in China. [4]. In Algeria, population growth is accompanied by a growing demand for infrastructure to meet these needs. As a result, the number of construction sites in the field of construction is increasing significantly, increasing the amount of inert waste generated, according to a study implemented by the National Waste Agency. The annual production of inert waste from construction field amounted to approximately 11 million tonnes in 2016 [5]. According to a projected scenario, this production is expected to reach an estimated 27 million tonnes by 2035. Various forms of garbage pose significant difficulties at the end of their lifecycle. A significant quantity of concrete waste is generated as a result of the demolition of ancient concrete edifices. The most common way of disposing of concrete waste is by its deposition in landfills, which causes significant environmental impacts and serious hazards to health [6]. Reusing this material offers the potential to preserve natural resources, thereby improving the sustainability of construction projects [7]. One of the techniques used to protect the environment is recycling inert waste in construction by reusing such materials. Utilizing recycled concrete aggregates (RCAs) is considered as the most efficient method of decreasing the worldwide need for natural aggregate. [8]. This approach has two significant advantages. It helps to reduce the accumulation of debris, which is essential mainly since inert waste constitutes a significant portion of solid waste, and contributes to preserving the environment's visual appeal and ecological characteristics. Also, recycling and reusing construction and demolition waste can reduce energy demand and CO2 emissions. [3,7,8]

Recycled aggregates are characterized by a gang of cementitious paste that adheres to the surface. The principal distinction between RCAs and natural aggregates is the adhering mortar and cement paste. The presence of this adhesive layer on the cover leads to a reduction in the mechanical and physical characteristics of aggregates, in particular their density and ability to resist fragmentation, while at the same time increasing their water absorption capacity. Several researchers have confirmed these findings [9-11]. This study investigates the impact of recycled concrete aggregate (RCA) on the mechanical properties of roller-compacted concrete (RCC) mixes. The research covers a variety of RCC mix designs with both natural and RCA materials. RCC is a type of concrete that can withstand a roller's compaction while remaining unhardened.[12]It consists of the same constituents as conventional concrete, in different ratios: cement materials, both fine and coarse aggregates, water, and, if necessary, chemical admixtures.[13,14] It is typically laid by asphalt pavers and compacted using vibratory rollers, and a similar slump cannot measure its workability because it has zero slump. The workability or consistency of this type of concrete is frequently evaluated using a vibrating table test. This test involves measuring the vibratory time, which refers to the period of vibration required to create a mortar ring inside the specimen[15]. Multiple parameters, including aggregate gradation, water content, cement content, additive content, and the presence of admixtures, may impact the consistency of a roller-compacted concrete (RCC) mixture [16,17]. The first use of a non-slump mixture goes back to the 1960s, with the construction of the Alpe Gere dam in Italy and the Manicouagan I dam in Canada. However, it wasn’t until 1970 once the subject became more appealing when Raphael presented an edit for the "optimum gravity dam" concept. After a considerable amount of ten years focused on research and development in different countries of the world, dam building with RCC was acknowledged as the most economical approach[12]. RCC mixes usually have a lower cement content than conventional concrete. This considerably reduces problems caused by the heat of cement hydration. In addition to their positive economic impact, these properties also contribute to the reduction of CO_2 emissions and atmospheric pollution. [13,18,19]. The significant growth and widespread application of this particular type of concrete it’s due to the exceptional performance and low cost compared with other types of concrete. According to an economic study, the initial cost of roller compacted concrete RCC pavements is approximately 30% less than that of conventional asphalt pavements and around 10 to 20% lower than the costs of conventional Portland cement concrete pavements [13]. The RCC is now used in many constructions, including dams, heavily trafficked roads, highway borders, city streets, and rural highways. In industrial applications such as wood storage areas, port infrastructure, storage car parks, sheds, and airport corridors. [20-23].

The study involved the use of recycled aggregates obtained from a landfill as a replacement for natural aggregates in the production of roller-compacted concrete. Eleven different formulations have been developed by varying the proportion of recycled aggregates, both with and without treatment, in order to assess the effect, the quality of recycled aggregate Furthermore, adjustments were made to the cement content by incorporating silica fume and slag at a 5% substitution rate. The primary aim of this is present research is to improve the mechanical properties of the concrete. The purpose of these formulations was to evaluate the impact of different quantities of recycled aggregates on the physical and mechanical characteristics of concrete at different levels of replacement.

2.Methodology

2.1. Material

A combination of materials was employed to prepare RCC specimens for this study. These materials included water, cement, natural aggregates (NA), recycled aggregates (RA), a setting retardant, silica fume, and slag. Also, two types of aggregate were employed.

2.1.1. Cement

The present research takes into account the use of Portland cement CEM II/B L 42.5 N, which was obtained from the LAFARGE firm in Algeria. A dosage of 300 kg/m^3 was used in all the mixes. Cement's Blaine surface was 4238 m^2/kg, and its bulk density was 3013 kg/m^3. Table 1 presents the chemical composition.

Table1. Characteristics and composition of the used cement

Fe_2O_3 (%)	SiO_2	Al_2O_3 (%)	SO_3 (%)	MgO (%)	CaO (%)	LOI (%)	K_2O	Free CaO	NaO_2	Vol. masse (g/cm^3)	Specific surface Blaine (cm^2/g)
2.88	17.45	3.99	2.26	1.66	61.51	10.75	00	1.71	0.52	3,01	4238

2.1.2. Mineral Additive

Silica Fume

The silica fume used in the present investigation is a grey powder acquired from microsilica sourced from the GRANITEX firm. Analysis shows that the surface has a mass of 19785 g/cm^2 and a density of 2.23 g/cm^3

Slag

The blast furnace slag used in this research is sourced from the El Hadjar steel plant. The substance has a density of 2.8 g/cm^3 and a Blaine-specific surface area measuring 3600 cm^2/g.

2.1.3. Chemical Admixture

This study used a setting retarder (SR) as a chemical admixture. The SR serves the purpose of reducing water content. It is known as "SIKA PLASTIRETARD" in Algeria. Table 2 provides an overview of the properties associated with this SR.

Table 2. Properties of the chemical admixture used

Density	1,175 ±0,015
PH	8,5 à 10,5
Chloride continent	≤ 0,1%
equivalent sodium oxide	≤ 6,0%
Dry solid content	31±2%

2.1.4. Natural Aggregates

Sand and natural aggregates were extracted from the Ouled Sidi Brahim M'sila quarry. The sand had a diameter of 4 mm. Crushed rock and coarse natural limestone aggregates (NA) varied in size from 4 to 20 millimeters. Figure 1 presents the distribution of particles used for this project: (3/8), (8/15), and (15/20).

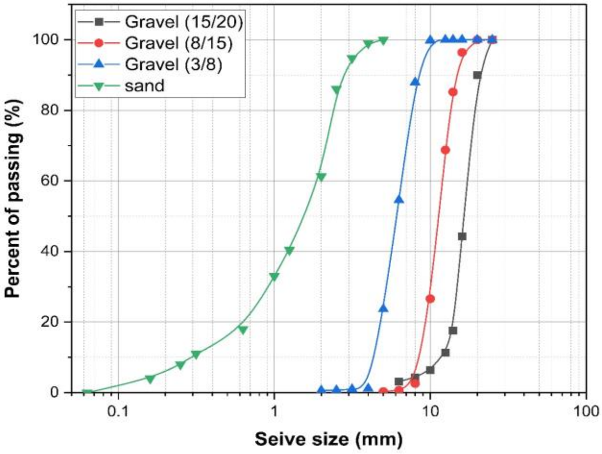

Fig. 1. The granulometric curve of the NA used

2.1.5. Recycled Aggregates

The recycled aggregates came from Algeria's Hamici Zerlada landfill (Fig.2). The aggregates recovered are crushed demolition and deconstruction concrete aggregates that have been recycled. A procedure was implemented to achieve the desired fractions of recycled aggregates by cleaning and washing the recycled waste. The process involved the removal of plastic, glass, and wood contaminants, resulting in a clean material ready for further processing.

Fig. 2. Recycled aggregates recovered from Construction and Demolition Waste (CDW)

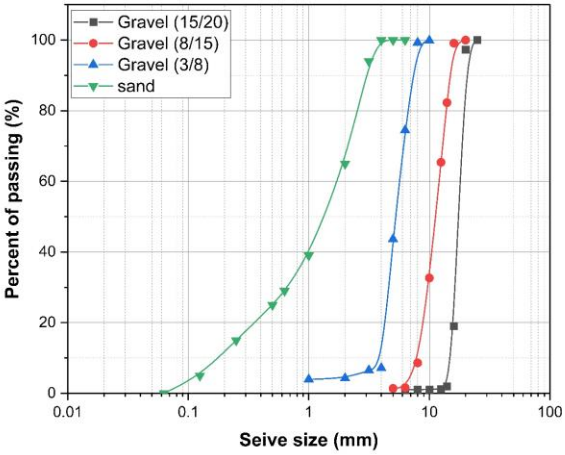

Fig. 3. Particle size distribution curves of the RCA used

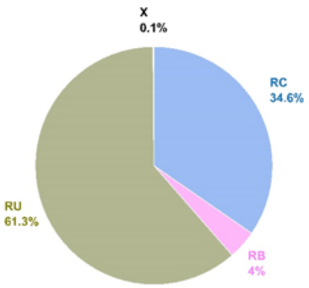

Fig.4. composition of recycled aggregate in accordance with standard EN 933-11

Table.3 Properties of natural and recycled aggregates

Properties	NA			RA			NS	RS	Test method
	3/8	8/15	15/20	3/8	8/15	15/20			
Absolute volumetric mass (kg/m^3)	2,73	2,71	2,83	2,72	2,72	2,69	2,72	2,69	EN12697-6
SSD density (g/cm^3)	2,65	2,64	2,75	2,50	2,53	2,53	2,64	2,47	EN12697-6
Water absorption (%)	1,65	1,41	1,30	5,43	4,58	3,91	1,78	5,52	EN12697-6
Acid-soluble sulphate content (% SO3)	0.0011			0.9898			-	0.8446	EN 1744-1
% MO	0.7512			2.7272			0.4003	4.9222	EN 1744-1
Sand equivalent	_	_	_	_	_	_	71.43	60,65	EN 933-8
Los-Angeles (%)	29.5			33.83			-	-	EN 1097-2
Micro-Deval (%)	12.96			34.4			-	-	EN 1097-1

Table 4. RCA composition according to EN 933_11

Composition	%
R_c: Concrete masonry units, mortar, and concrete-based materials	35
Ru: Aggregates that have been treated with hydraulic binders include untreated gravel and natural stone.	62
R_b: Clay materials, such as bricks and tiles	4
Masonry made of calcium silicate	
Aerated concrete that is not floatable	
X: Other: Cohesive, Miscellaneous: metals (ferrous and non-ferrous)	0,13
R_g: Glass	0

The rubble was then sieved through a 20-mm sieve to eliminate rejected particles. Subsequently, a series of sieves were used to obtain the four desired fractions: sand (0/4), aggregates (3/8), (8/15), and (15/20). However, because of its high capacity for water absorption and less desirable chemical properties, including a high organic material content compared to standard recommendations, it was determined that recycled sand would not be used in this research. The mechanical, chemical, physical, and characteristic properties of these materials are given in Table 3. Table 4 and Figure 4 present the composition of recycled aggregates as described in the standard [24].

2.2.Mix Design

In order to reach the main objectives of this research, a total of eleven mixtures were prepared. Table 4 presents the proportions of each mix investigated in this study. Roller-compacted concrete (RCC) should be between 12% and 16% of its dry mass made up of cementitious materials, according to research that has already been done and best practices for mix design [12], [13], [20], [25] . To carry out this study, a mean of these factors was chosen, and the cementitious material content stayed at 15% throughout all mix proportions. This includes cement and other cementitious materials like slag and silica fume. In this study, the RCC mix had a cement content of 15%.The LCPC laboratory conducted a compaction test on a shake table to determine the relative proportions of the various aggregate classes, aiming to improve the density of the mixture. [26]This experiment test assesses the degree of compactness of a defined granular mass fraction when subjected to a standardized mechanical load within a cylindrical container. After determining the compactness of each class, tests were conducted to determine the maximum compactness of each mixture. These tests assessed the compactness of both recycled and natural granular mixtures. Subsequently, the fractions were quantitatively analyzed and compared to the recommended granular spindle outlined in the standard [25]. This evaluation was carried out to verify whether the mixtures adhered to the specified standards, ensuring optimal compactness. Figure 5 shows the aggregates' granulometry and the upper and lower limits determined by the standard [25] .

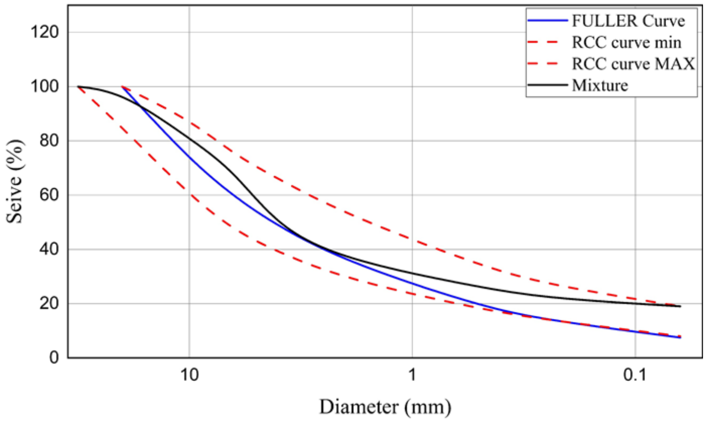

Fig. 5. Mixing curve used for the present research

After estimating the aggregate quantities, the cement dosage was determined to be 300 kg/m^3. The water quantity was calculated using the Proctor-modified standard [27]. In general, the cement content of RCC pavement ranges from 8% to 12% [12], [25] .For this study, a cement composition containing 15% of cement was used. The compressive strength test showed that a cement concentration of 300 kg/m^3 and an optimal water content of 5.3% reached the best compressive strength for RCC after seven days. Table 5 presents full details about each concrete mix, including the specific composition, proportions, and water/cement (W/C) ratios.

Table. 5. The groupings, titles, proportions, water/cement ratios, and material for each mix

Type of concrete	W/C	NG (%)	RG (%)	NS (%)	Proportions (kg/m³) 3/8N	3/8 R	8/15N	8/15R	15/20 N	15/20 R
RCC0	0,46	100	0	986	495	0	356	0	144	0
RCC25	0,48	75	25	986	371	124	267	89	108	36
RCC50	0,50	50	50	986	248	248	178	178	72	72
RCC75	0,53	25	75	986	124	371	89	267	36	108
RCC100	0,54	0	100	986	0	264	0	386	0	259
RCC25SF	0,48	25	75	986	371	124	267	89	108	36
RCC50SF	0,50	50	50	986	248	248	178	178	72	72
RCC25S	0,48	25	75	986	371	124	267	89	108	36
RCC50S	0,50	50	50	986	248	248	178	178	72	72
RCC25 PREW	0,41	25	75	986	371	124	267	89	108	36
RCC50PREW	0,42	50	50	986	248	248	178	178	72	72

The procedure for mixing the eleven mixtures consisted of using a concrete mixer. The mixtures were divided into three different groups. The first group included five mixtures in which the aggregates were substituted with different proportions of recycled aggregates: 0%, 25%, 50%, 75%, and 100%.

Table. Mixing method

1 minute of mixing	1 minute of mixing	1 minute of mixing	2 minutes of mixing	0 min
Aggregates	Cement	rest	Water + adj	Mix

In the second group of experiments, additional silica fume (SF) and slag (S) were added at a proportion of 5% to replace cement in the concrete mixtures, which contained 25% and 50% recycled aggregates. Finally, the third group was subjected to a preliminary pre-wetting (PREW) treatment of recycled aggregates for 48 hours before being implemented into the mixtures, which contained 25% and 50% recycled aggregate following the mixing protocol described in Table 6. After mixing, as described in the table above, the concrete was placed in the cubic moulds in four layers, while the prismatic moulds received the concrete in two layers.

Fig. 6. The vibrating hammer employed for compacting the RCC specimens

The concrete specimens were made using cubic moulds with dimensions of 150 mm × 150 mm and prismatic moulds of 70 mm × 70 mm × 280 mm. Before its use, the moulds underwent a rigorous cleaning procedure and were then treated with oil to eliminate impurities and mitigate the adhesion of concrete to the interior surfaces of the moulds. Fresh concrete was introduced into cubic, prismatic, and cylindrical moulds, then compacted using an electric vibrating hammer with square, rectangular, and circular plates, according to[28] the cast specimens were retained inside the moulds for 24 hours. Subsequently, the moulds were recovered, and the specimens were subjected to a controlled humidity environment for seven, twenty-eight, and ninety days. Three specimens were used for each test.

3. Results and Discussion

3.1. Vebe Time

Consistency is the main factor in determining the buildability of RCC. Because of its stiff to extremely dry consistency, the standard slump test with an Abrams cone is not applicable to this type of concrete. The vebe test[15] is generally used to evaluate the consistency of an RCC mixture. According to the ASTM C1170 Standard Test, in the case of roller-compacted concrete, workability corresponds to the compaction energy required to consolidate the concrete in its fresh state adequately [29]. The procedure consists of placing the specimen of the RCC in a cylindrical mould fixed on a vibrating table figure 7. An overcharge of 22.7 kg is placed on the top of the material. The vebe time is the time of vibration when a mortar ring is observed around the total perimeter of the surcharge.

Table 7. The mean values of compressive, flexural, ultrasonic pulse and vebe time

Mixtures	Compressive strength (MPa)			Flexural strength (MPa)			Ultrasonic pulse velocity (m/s)		
	7days	28 days	90 days	7days	28 days	90 days	7days	28 days	90 days
RCC$_{0}$	46,25	56,47	60,41	8,86	9,46	10,30	4941,15	4970,43	5220,61
RCC$_{25}$	44,74	53,98	59,94	8,39	8,79	9,58	4865,27	4875,82	5102,63
RCC$_{50}$	43,17	51,06	53,26	7,47	8,72	8,82	4687,55	4871,36	4852,40
RCC$_{75}$	38,49	46,58	50,62	7,73	8,80	8,86	4604,99	4737,66	4732,51
RCC$_{100}$	36,48	40,29	47,39	6,92	7,87	8,64	4592,37	4634,04	4713,5
RCC$_{25SF}$	41,48	53,29	56,58	8,02	8,75	8,88	4931,10	4904,55	5180,98
RCC$_{50SF}$	41,53	45,69	57,91	7,90	8,70	8,75	4854,89	4876,3	4988,33
RCC$_{25S}$	40,71	47,34	57,66	8,23	8,51	8,81	4886,95	4840,77	5025,59
RCC$_{50S}$	37,20	46,79	57,10	8,09	8,14	8,44	4836,41	4869,53	5021,53
RCC$_{25PREW}$	44,49	45,69	55,05	8,75	8,94	8,7	4719,821	4928,374	4942,146
RCC$_{50PREW}$	41,16	45,06	51,64	7,07	7,73	8,63	4607,993	4808,467	4855,437

The table below displays the test results, demonstrating the variation in vebe time with the proportion of recycled aggregate substitution. The objective in designing RCC mixtures is to achieve a blend that provides maximum dry density and suitable consistency (vebe time ranging from 30 to 75 seconds). A few lab tests show that a changed vebe time of 30 to 40 seconds for RCC pavement mixtures, measured with a 50-lb (22.7 kg) extra charge, works much better[19] . To investigate the consistency of roller-compacted concrete (RCC) mixes, through modified vebe tests, the process is conducted ten minutes after the casting process, following the ASTM C 1170 standard.

Fig. 7. Vebe test Apparatus for evaluating consistency of fresh RCC

The primary objective was to evaluate the impact of recycled aggregate substitution on the consistency of RCC mixes. The test results, as presented in Table 8, revealed that increased recycled aggregate substitution led to higher optimum water contents. Furthermore, it was observed that the vebe times for mixtures with a high substitution of recycled aggregates decreased when compared to the control specimen. This was due to the mixtures having a higher optimum water content. In the context of the vebe test, a decrease in the vebe time reflects a wet consistency of the mixture, while an increase in this parameter indicates a dry or rigid mixture consistency. The comparison of vebe time between the two concrete mixes, RCC_{75} and RCC_{50SF}, shows that water quantity, aggregate gradation, and fine content have a significant impact.

Table 8. The results of Vebe time

Mixes	Vebe time(s)
RCC_{0}	43
RCC_{25}	42
RCC_{50}	39
RCC_{75}	36
RCC_{100}	31
RCC_{25SF}	43
RCC_{50SF}	40
RCC_{25S}	41
RCC_{50S}	35
RCC_{25PREW}	30
RCC_{50PREW}	28

The vebe time for RCC_{50} is 36 seconds, while for RCC_{50SF}, it is 40 seconds. The difference suggests that the mixture with a greater number of fines takes longer to settle and compact, possibly due to the increased surface area of the fine particles. These results are consistent with the findings obtained by [16], who found a decrease in vebe time with increased water content. Using silica fume in RCC_{0} and RCC_{25SF} mixtures resulted in the highest vebe time of 43 seconds. This oddly contrasts with the impact of slag on the consistency properties of RCC mixtures. The addition of silica fume resulted in the mixtures becoming drier, which in turn led to a longer compaction time. This finding suggests that using silica fume in RCC mixtures may pose challenges to fieldwork. This result is based on research by [30], who observed an improvement in the workability of mixes with 30% pumice substitution, recording an average time of 69 seconds.

In comparison, they recorded an average time of 88 seconds for the C12S10 mix. These findings confirm the observations regarding the use of silica fume. As the substitution of aggregates increases, the vebe time tends to decrease. The RCC$_{50PREW}$ mix has the lowest vebe time of 28 seconds. This reduction may be attributed to the residual water content in the recycled aggregates after pre-wetting them before adding them to the mix. The pre-wetting makes up for the high-water absorption. However, studies have noted that excessive mixing, typically lasting longer than 30 seconds, can lead to segregation in recycled aggregate concrete[31], increased by the compaction vibration from the vibrating hammer. The vibration effect causes the water stored in the aggregates to come out and envelop them, resulting in an excess film of water covering the aggregates. This excess water leads to a higher workability of the concrete, which sets it apart from other mixes and explains the reduction in vebe time. This result aligns with previous research [32], which identified a loss of workability with the increasing substitution of recycled aggregates with the same ration (w/c). The higher water absorption of concrete waste compared to natural aggregates could be the cause of this workability loss.

3.2. Density

It is important to note that RCA may have a lighter specific gravity and may contain adhered old cement mortar, contributing to the reduced density of concrete containing RCA. [33], [34] Researchers suggest that the low specific gravity of recycled concrete aggregates (RCA) may be attributed to the quality of virgin aggregates rather than the quantity of old cement mortar present [35], [36].

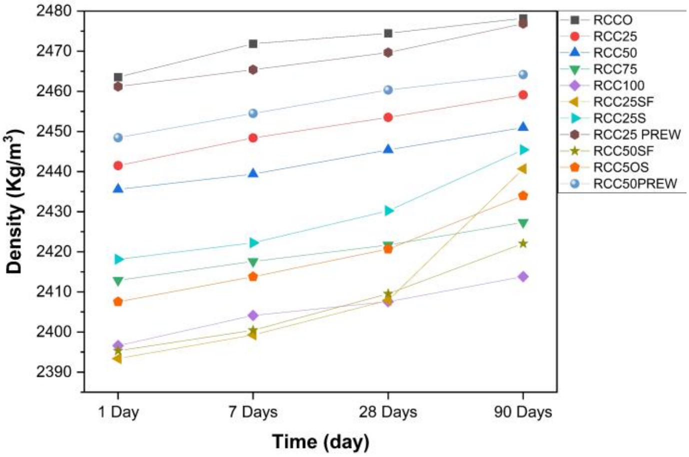

Fig. 8. Variation of the Density according to the rate of substitution of aggregates

During sample preparation, it was observed that integrating recycled aggregates (RA) had a little influence on the wet density. The following figure illustrates the density evolution by substituting recycled aggregates over time. As depicted in Figure 8, the highest density is for the natural aggregate concrete. A decrease of around 3% was observed for the RCC$_{100}$ mix over time, decreasing as the substitution rate increased. A 1% and 2% decrease for the RCC$_{25}$ and RCC$_{50}$ mixes, respectively, was noted. This decrease is attributed to the properties and quantity of the substituted recycled aggregate. The mortar paste adhered to the aggregate makes the density of the aggregate lower than a natural aggregate [37], and this is due to the porosity of the interface between the two materials. However, the RCC 50$_{PREW}$ mix showed a minor decrease in density due to the pre-wetting process, during which recycled aggregates are saturated before being incorporated into the concrete. The RCC$_{25SF}$ and RCC$_{25S}$ mixes decreased due to the substitution of recycled aggregates and the addition of cementitious materials. Some previous studies on recycled concrete confirm what has been mentioned above. In their study, Maleseva et al. [10] noted a reduction in wet density as the amount of recycled aggregate increased. This effect was observed to be approximately 3% when recycled aggregates entirely replaced natural aggregates. Similar outcomes were reported by [38], indicating a significant reduction in fresh density of approximately 11% due to an increase in the 100% recycled aggregate substitution rate. Furthermore, a decline in the hardened density of approximately 6% was observed in concrete specimens that contained 100% recycled aggregate. Other research developed by Zaetang et al. [39]discovered a 5% decrease in density for concrete substituted with 100% recycled aggregates compared to control concrete. Abraham et al. [40][40] found that as recycled aggregates and fines increased, the fresh density of concrete decreased by approximately 2% and 5%, respectively.

Similarly, the density of hardened concrete dropped by about 5% and 10% for mixtures replaced with 100% recycled granulates without fines and with fines, respectively, after 28 days. Marta Sánchez et al.[37]found that old mortar on recycled aggregates affects concrete density, with increased mortar causing a decrease. Angel Salesa et al.[41] found a 2.54% decrease in SSD for 2nd generation recycled aggregates and 1.45% for RC1, with a 4.03% reduction in dry density compared to control concrete. The above study found that the difference in density depends on the type and amount of aggregate used. The lower specific gravity of the cohesive mortar layer on top of the aggregates causes the density to drop down.

3.3. Compressive Strength

Three groups were tested to evaluate the influence of recycled aggregates (RCA) on the compressive strength of roller-compacted concrete mix (RCC). Ninety-nine cubic specimens with 150 mm x 150 mm dimensions were prepared and subjected to compression testing to assess their resistance at three different periods: seven days, 28 days, and 90 days. These tests were performed according to [42] standards after the curing period, during which the samples were kept in a moist room at 22 °C with a relative humidity of 92%. After the curing period, three samples of each mixture were subjected to testing. The load was applied perpendicular to the surface of the concrete during compaction.

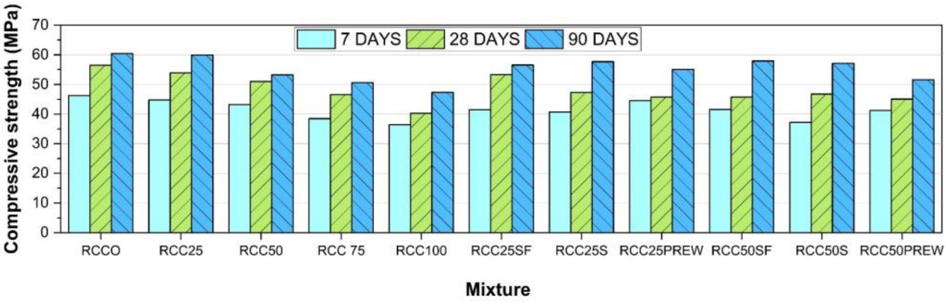

Fig. 9. Compressive strength of Roller-Compacted Concrete (RCC) at various substitution rates

According to the substitution rate, the average 28-day compression resistance losses for RCC mixtures with recycled aggregate compared to RCC mixtures with 100% natural aggregates with a 25% progression were 7%, 10%, 18%, and 29%, respectively. The data from Table 7 and Figure 9 indicates that the mixes with a pre-wetting treatment displayed less favorable results when compared to those without a pre-wetting treatment. A decrease in compressive strength of approximately 12% for the RCC_{50PREW} mixture was observed compared to the untreated RCC_{50} mixture, and a decrease of about 11% for the RCC50S and RCC50SF mixtures compared to RCC_{50}. The higher (w/c)ratio and the inclusion of silica fume and slag in the RCC_{50} mix, which had no impact at the 28-day age, contributed to the latter's strength decrease. It is noteworthy that the inclusion of 5% SF did not affect the compressive strength results of these mixtures. Table 7 presents the compressive strengths of different mixtures after 7, 28, and 90 days of curing. In consideration of the substitution rate, the average 7-day compression resistance losses for RCC mixtures containing 100% natural aggregate until RCC mixtures containing 100% recycled aggregates with a 25% progression were 3%, 7%, 16%, and 22%, respectively. Mixtures containing recycled aggregates, silica fume, and slag exhibit reduced strength due to aggregate substitution and the water-cement ratio(w/c). Experiments tests show that the addition of 5% silica fume and slag has an insignificant effect on strength. It was observed that RCC_{25SF}, RCC_{50SF}, RCC_{25S}, and RCC_{50S} mixes became weaker after 7 and 28 days compared to the reference concrete, indicating a decrease in strength. At seven days, the decreases were 10%, 11%, 12%, and 20%, respectively, while at 28 days, they were approximately 12%, 20%, 16%, and 18%, respectively. Notably, using 5% SF and 5% slag had no significant impact on the compressive strength results. Resistance improved after 90 days of age when mixtures were replaced with silica fume, indicating increased resistance. The decrease amounts to approximately 4% in comparison to the control concrete. The enhancement is due to its high reactivity and pozzolanic qualities, which improve the microstructure of the cement paste and reinforce the link between the aggregates and the cement by closing voids in the concrete [43], [44]. A study by Farshid et al.[30] showed similar results. They showed that replacing 10% of the cement with silica fume (SF) increased the compressive strength of roller-compacted concrete. In contrast, a 5% substitution had no significant effect on strength. Another study [45] documented an increase in the compressive strength of roller-compacted concrete (RCC) with the addition of silica fume (SF). However, another reference [46] reported similar results at a 10% SF cement replacement. For comparative analysis, more research is needed regarding the use of a blend of RCA and slag in the production of RCC. Most existing studies have focused on using RAP or RCA in conjunction with silica fume. The results indicate that a low percentage of slag does not significantly improve resistance. The figure's representation indicates that mixes subjected to a pre-wetting treatment exhibited lower results compared to non-treated mixes.

The RCC_{50PREW} mixture exhibited a 12% reduction in compressive strength compared to the untreated RCC_{50} mixture. Similarly, the RCC_{25PREW} mixture demonstrated an 11% decrease in compressive strength relative to the RCC_{50} mixture. The reduction in strength of recycled concrete aggregates (RCA) can be attributed to various factors, such as the properties of the mortar matrix and the interfacial transition zone (ITZ). The presence of old mortar affects the bond between the aggregate and the new cement in the mix, leading to weakened ITZ behaviour and a subsequent reduction in strength. Additionally, recycled aggregates have high absorption, and the pores in the old mortar weaken the aggregate compared to natural aggregates, resulting in lower density and a higher susceptibility to fragmentation. This ultimately affects the mechanical properties of concrete made with recycled aggregates. When compared to the results of McGinnis et al., who noticed a decrease in strength of around 16 to 26% for substitution rates of 50% and 100%, respectively, similar trends are evident. Other references [34], [47] that reported similar results attributed the strength loss to variations in humidity, the water-to-cement (W/C) ratio, and the mixing method. These factors all significantly affect compressive strength, causing a substantial decrease after seven days of curing. Vivian et al.[48] attributed the loss in strength to the mixing method, where they observed a 20% improvement in compressive strength using a two-stage mixing approach (TSMA) compared to normal mixing (NMA), which strengthens the interfacial bond. These results are consistent with the findings of [49]. According to the American Concrete Institute (ACI) 325-10R[19], roller-compacted concrete pavements must exhibit a minimum compressive strength of 27.6 MPa after 28 days. According to the data in Table 7, all the mixes achieved the specified limiting level at 28 days.

3.4. Flexural Strength

In order to assess the mechanical properties of a mixture, an experiment test was conducted in accordance with EN standard 12390-5 [50]. The test involved using three prismatic specimens with dimensions of 7x7x28, which were subjected to a three-point bending moment. During the testing process, the force was applied perpendicular to the surface of the compacted specimens. Testing was carried out at three intervals: seven, twenty-eight, and ninety days. The mean of three measurements was calculated for each specimen, and the results are presented in Table 7. The experiment test was implemented to evaluate the performance of the mixtures for flexural strength over time.

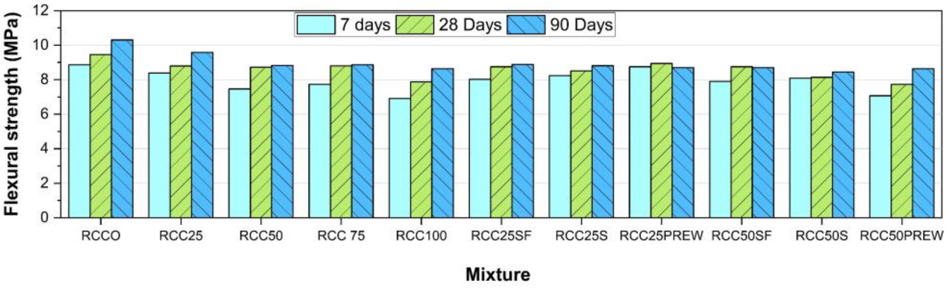

Fig. 10. Flexural strength of Roller-Compacted Concrete (RCC) at various substitution rates

The graphical representation illustrates the flexural strength results of various concrete mixtures. Particularly, the concrete compositions that exhibited the most substantial declines in strength were RCC_{100} and RCC_{50PREW}, with a recorded decrease of 22% and 21%, respectively, compared to the control concrete at seven days of curing. Conversely, the control mixes, namely RCC_0 and the mixtures RCC_{25}, RCC_{25SF}, RCC_{25S}, and RCC_{50PREW}, showed the highest resistance values. Within the first seven days, the reduction in strength was relatively minor, ranging between 3% and 5%. However, RCC_{100} experienced a decline of 17% at the 28 and 90-day marks. It is worth emphasizing that the reduction in strength diminishes over time, with the control concrete exhibiting the maximum strength characteristics among all the mixes. The study's results reveal a close relationship between the concrete's flexural strength and compressive strength, which decreases as recycled aggregates are substituted. However, the decline in strength is comparatively less pronounced than the compressive strength. The concrete mix that included recycled aggregates, identified by RCC100, recorded a 29% reduction in strength compared to the concrete used as a control. A previous study [46] observed a decrease of approximately 36% in flexural strength, which aligns with these findings. In comparison, compressive strength suffered a decline as high as 70%. According to a study conducted by R.Kumar[51], similar results were found, with a decrease of 20% observed in the mix made with a small recycled granular class, possibly due to the negative impact of cementitious paste on strength. As previously mentioned, a mortar layer attached to the recycled aggregates creates a transition zone (TZ) between the natural aggregates and the cementitious paste, there by influencing the properties of new concrete. The use of recycled aggregates in new concrete results in the creation of a new interface that is directly affected by the moisture content and characteristics of the old concrete. Consequently, the resulting concrete shows a decrease in its overall characteristics and increased water absorption. These findings are compliant with those of earlier studies, such as the ones presented by[28] . Based on the guide for roller-compacted concrete pavements[52] ,the flexural strength of pavement concrete varies between 3.5 and 7 MPa at 28 days. As shown in the figure, the results obtained for the eleven mixes prepared meet the required values, indicating that using recycled aggregates is desirable in pavement concrete.

3.5. Ultrasonic Pulse Velocity

All the concrete samples were subjected to UPV evaluation after being cured for 7, 28, and 90 days. To calculate the velocity of the waves, The distance between the transducers was equivalent to the width of the concrete specimen, which measured 150 mm, was divided by the measured time. Each specimen was examined five times, and the mean values of the results was taken in consideration.

Three cubic samples (150×150×150) mm3 were used for each mixture to determine the ultrasonic pulse velocity. The results for each mixture are the average of three samples at 7, 28, and 90 days. The results of the non-destructive ultrasonic wave propagation test were obtained from the test conducted by EN 12504-4 [53], Figure 1 illustrates the evolution of concrete mixtures' ultrasonic pulse velocity (UPV). It is quite evident from the image that when recycled aggregates substituted natural aggregates, the UPV of concrete mixtures decreased at all test ages.

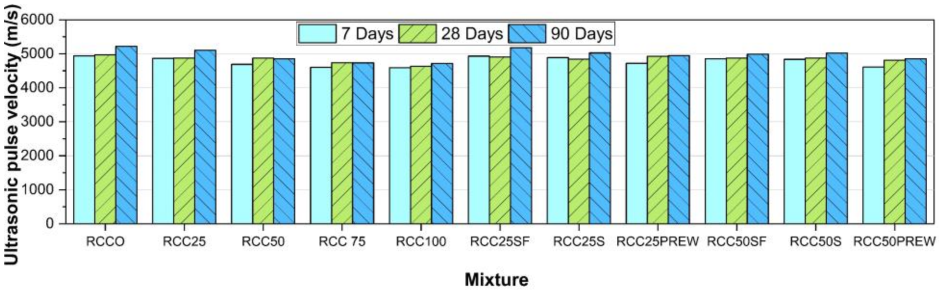

Fig. 11. Progression of UPV with time for RCC mixes

This reduction correlates with the previous mechanical strength findings, in opposition to the results obtained by [54], who noticed a decrease in ultrasonic pulse velocity as strength increased. The results showed a decrease in UPV for concrete with recycled aggregates. The decrease in UPV was significant, with values of 5%, 9%, and 10% for concrete with 50%, 75%, and 100% substitution, respectively, in comparison to the control concrete. However, the decrease was less pronounced for concrete containing silica fume and slag, with a decrease of 3% for RCC$_{50S}$ and RCC$_{50SF}$ mixtures compared to the control concrete. Based on the findings, it has been observed that the ultrasonic pulse velocity (UPV) of concrete manufactured with recycled aggregate tends to decrease. This can be explained by the fact that recycled aggregate typically has a lower density and greater porosity than natural aggregate. The presence of voids and pores in recycled aggregate leads to a higher degree of attenuation and scattering of ultrasonic waves, thereby reducing UPV values. These findings highlight the need for appropriate selection and processing of recycled aggregates to ensure their compatibility with the desired concrete properties. The velocity of ultrasonic pulses that travel through a solid material depends on the material’s thickness and elastic properties.

4. Conclusion

This study has provided empirical evidence supporting using recycled concrete aggregate as a sustainable option for creating new roller-compacted concrete. Its shows that using this method can result in significant reductions in waste production while maintaining similar performance qualities as conventional concrete. The results have potential implications for the construction industry, where the adoption of environmentally friendly techniques is becoming more important. The results obtained from this experimental study led to the following conclusions:

The incorporation of recycled aggregates in concrete is associated with a reduction in its compressive strength. This decrease in strength has been observed to become more pronounced with increased substitution rates However, it is important to note that despite the decrease in strength, the recommended mechanical strengths for roller-compacted concrete were met for all substitution percentages.

- The substitution of aggregates in roller-compacted concrete (RCC) mixes with recycled materials leads to higher optimum waters contents. Additionally, the vebe times tend to decrease as the substitution of aggregates increases, with silica fume mixtures having the longest Vebe times and RCC_{50PREW} mix having the lowest vebe time. This decrease in vebe time is mainly due to the water retained in recycled aggregates and the compaction vibration of the vibrating hammer.
- The moisture content and characteristics of the old concrete have an impact on the new interface that recycled aggregates introduce. This alteration leads to a decrease in the overall characteristics of the concrete.
- Based on the results it has been found that the mechanical properties of concrete remain comparable to those of the control with up to 50% substitution of recycled aggregates. However, beyond this substitution level, there is a noticeable decrease in strength and properties.
- The use of recycled aggregates in concrete production lead to a significant decrease in ultrasonic pulse velocity (UPV), which is mainly due to the lower density and higher porosity of these aggregates compared to natural ones. However, the addition of silica fume and slag can mitigate this decrease to some extent
- Using recycled aggregates in making concrete can result in a gradual reduction in density over time. The RCC0 had the maximum density, and the RCC_{100} had the minimum density, with a 3% decline detected as the substitution rate fell. The drop in density is due to the properties and quantity of the substituted recycled aggregate and the amount of mortar attached to the recycled aggregates used as a substitute.
- The results demonstrate that the flexural strength is comparable to the compressive strength. The study also revealed that the strength of the material decreases with an increase in the substitution of recycled aggregates. However, the drop in strength is less pronounced in flexural strength compared to compressive strength

Based on the positive results obtained from using recycled aggregates in this study, it can be confidently concluded that concrete created with these materials is suitable for practical applications. Utilizing waste by recycling aggregates, rather than using new materials, contributes to the attainment of sustainable development objectives and provides substantial cost reductions in construction. Furthermore, using recycled materials reduces environmental damage and conserves natural resources for subsequent generations.

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