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Prediction of compressive strength based on durability parameters of roller-compacted concrete using recycled pavement materials

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Abstract:
This study examines the mechanical and durability performance of roller-compacted concrete pavement (RCCP) incorporating recycled asphalt pavement (RAP) as a partial or full replacement of natural aggregates (NA) (0–100%). The replacement levels considered were 0%, 25%, 50%, 75%, and 100%. Concrete specimens were exposed to acidic and sulfate solutions (1% HCl, 3% H_2SO_4, 5% Na_2SO_4, and 5% $MgSO_4$) to simulate long-term environmental stress. Results showed RAP enhanced resistance to chemical attacks up to 50% substitution, while higher contents reduced compressive strength (CS) but maintained acceptable durability. An empirical model predicting CS as a function of exposure type and curing time showed a strong correlation with test results. This research confirms RAP as a sustainable alternative to natural aggregates, supporting resource conservation, waste reduction, and cost efficiency in pavement construction.

Keywords:
roller-compacted concrete, recycled aggregates pavement, compressive strength, durability, prediction model

1. Introduction

Pavements, whether rigid or flexible, play a fundamental role in global transportation networks [1,2]. They must meet multiple requirements, including resistance to heavy loads, durability under varying weather conditions, and adaptability to local traffic and environmental conditions. In this context, the choice of paving material is crucial. Rigid pavements, typically made of concrete, are known for their robustness and ability to withstand heavy loads without deformation.

Each pavement type has advantages and limitations that depend on several local factors, such as traffic intensity, climatic conditions, and economic constraints [3]. For example, concrete pavements are ideal for infrastructure subjected to heavy traffic due to their stability and resistance to wear. However, they have notable drawbacks, including high costs and regular maintenance requirements, which may necessitate more frequent rehabilitation work compared to asphalt pavements [4].

Conversely, flexible asphalt pavements, while more susceptible to degradation from thermal variations and heavy vehicle traffic, are characterised by their flexibility. This characteristic enables better adaptation to ground movements and climate fluctuations while offering a more cost-effective short-term solution. However, their durability remains a challenge, as they are more prone to cracking and pothole formation [5].

An innovative material, roller-compacted concrete (RCCP), has emerged as a promising alternative to both rigid and flexible pavements. RCCP exhibits unique characteristics, including enhanced strength due to its low water-cement ratio and low water content, which grants it exceptional durability [6,7]. This material is particularly well-suited to extreme weather conditions and exposure to chemicals such as diesel [8]. Moreover, its ease of implementation and reduced need for heavy equipment can lower construction costs by 10–30% compared to conventional concrete [9]. RCCP also has the advantage of being made from recycled materials, thereby reducing its environmental footprint and promoting more sustainable construction practices [5].

At the same time, the use of reclaimed asphalt pavement (RAP) in concrete pavements represents a key solution for advancing the circular economy in construction [10-12]. By incorporating RAP into concrete mixes, it is possible to recycle previously used materials, reducing reliance on natural aggregates while minimising the environmental impact of the construction industry [13]. However, integrating RAP into concrete presents technical challenges, particularly due to the presence of bitumen, which interferes with the bond between recycled aggregates and cement, potentially affecting the mechanical properties of the concrete [14,15].

The increased use of recycled materials, such as RAP, aligns with the goal of enhancing sustainability in road infrastructure construction. This trend has accelerated in Europe since the 1973 oil crisis [4]. This shift is driven by growing environmental awareness and a desire to reduce waste and the carbon footprint of the industry [5]. However, further research is required to address the technical challenges involved in incorporating these recycled materials into concrete mixes to ensure their effectiveness and long-term durability in pavements [16,17].

In this context, the present study explores the feasibility of replacing natural aggregates with RAP in roller-compacted concrete (RCC) mixes. The primary objective is to assess whether this substitution can be achieved without compromising the mechanical properties and durability of the concrete while maintaining the required characteristics for road applications [18,19]. RCCP mixes were prepared by replacing natural coarse aggregates with increasing proportions of RAP (0%, 25%, 50%, 75%, and 100%). Performance tests, such as capillary absorption, porosity, and resistance to acid and sulfate attacks, were conducted to evaluate the durability of the mixes.

Concrete samples were prepared according to ASTM C267 [20] standards and cured for 28 days. To simulate aggressive environmental conditions, acidic solutions of 1% hydrochloric acid (HCl) and 3% sulfuric acid (H_2SO_4) were used. The impact of sulfate attacks was studied by immersing samples in 5% sodium sulfate (Na_2SO_4) and 5% magnesium sulfate ($MgSO_4$) solutions, following ASTM C1012-04 [21]. The samples were tested to assess their resistance to physical and chemical degradation, including crack formation and reduced mechanical strength under the influence of aggressive solutions [22].

The ultimate goal of this study is to propose a sustainable solution for constructing roller-compacted concrete pavements using recycled materials, thereby minimizing the environmental impact associated with producing new materials. This research aims to advance the valorisation of RAP in the production of RCCP with acceptable mechanical, physical, and durability properties. Furthermore, a new predictive model is proposed to estimate CS, incorporating parameters such as age, exposure solution type, and durability metrics.

2. Materials and experimental methods

2.1. Materials used

2.1.1. Aggregates

For this study, various types of aggregates sourced from local regions in Algeria were used. Natural sand with a grain size of 0/4 mm was extracted from the Oued Ras area in the Chlef province. Two types of gravel were also utilized: one with a grain size of 3/8 mm and another with 8/15 mm, both sourced from a quarry in the Relizane province. These materials were selected based on their availability and physical characteristics, which were suitable for the study.

The recycled asphalt pavement (RAP) materials were obtained from the national highway in the Relizane region after 18 years of service. The RAP was carefully collected, then subjected to crushing and sieving processes to prepare the particles for analysis.

A distinguishing feature of these aggregates is the hardened asphalt film coating the coarse particles, which influences their mechanical properties and behaviour in concrete mixtures. The asphalt content, calculated in accordance with ASTM D2172, is 5.5%.

The particle size distribution of these aggregates is illustrated in Fig. 2, while the physical properties of both natural aggregates (NA) and RAP are detailed in Tab. 2. These data provide a better understanding of the specific characteristics of each material used in this study and allow for a comparison of their performance in the tested mixtures.

Fig. 1. Milling of existing asphalt pavements

Table 1. Properties of the cement used

Chemical Analysis	
Parameter	Value
Loss on ignition (%)	11 ± 1
Sulfate content (SO_3, %)	2.4 ± 0.5
Magnesium oxide content (MgO, %)	Max 5%
Chloride content (Cl^-, %)	< 0.1
Specific gravity	3.12
Blaine fineness (cm²/g)	3850
Initial setting time (min)	145
Final setting time (min)	215
Mineralogical Composition	
Compound	Content (%)
C_3S (Alite)	60 - 70
C_3A (Tricalcium aluminate)	8 ± 2

2.1.2. Cement

For the experimental program, only one type of cement was used: Portland cement class CEM II/C-M (P-L) 32.5 R. This is a composite cement consisting of limestone and pozzolan. The cement was produced by the Oggaz cement plant, located in the Mascara province, and complies with both Algerian standards (NA 17092) [23] and European standards (EN 197-5) [24]. The physical and mechanical properties of this cement, which are crucial for mixture analysis, are detailed in Tab. 1. This cement was selected for its local availability and compliance with current standards, thereby ensuring the quality of materials used for the study.

Table 2. Study of RCCP formulation

Materials (Kg/m^3)	RCCP0	RCCP25	RCCP50	RCCP75	RCCP100
Cement	250	250	250	250	250
W/C	0.576	0.472	0.49	0.472	0.552
Sand 0/4	631.7	631.7	631.7	631.7	631.7
Gravel 3/8 N	258.5	193.9	129.3	64.6	/
Gravel 8/15N	976.1	732.1	488.1	244	/
Gravel 3/8 RAP	/	64,6	129.3	193.9	258,5
Gravel 8/15 RAP	/	244	488.1	732.1	976.1
W_{opt}	6.9	5.58	5.8	5.57	6.61
W_{opt}	6.9				
Absorption rate of RAP Absorption rate of NA					2.08% 0.97%

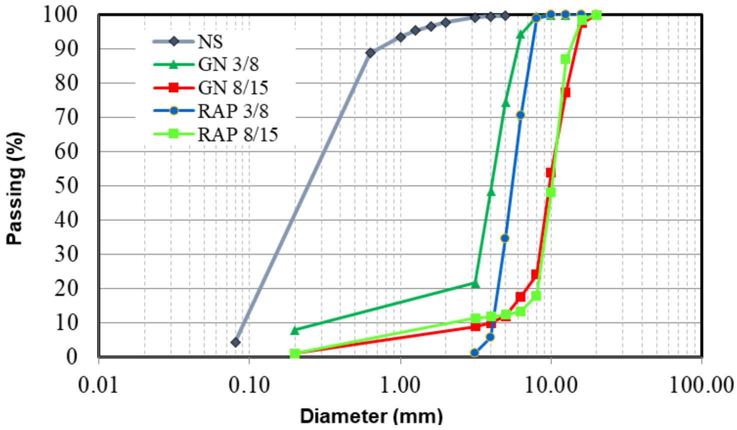

Fig. 2. Particle size distribution curve

Fig. 3. Aggregates used

3. Testing methods

3.1. Mixing and compaction

3.1.1. Preparation of specimens

The aim of this study is to evaluate the effect of RAP aggregates on the performance of roller compacted concrete (RCCP). Five mixes were made by varying the substitution rate of RAP (0, 25%, 50%, 75%, and 100%) for the 3/8 and 8/15 granular classes. A reference mix (0% RAP) was used as a control.

The preparation of the concrete was conducted by adjusting the proportions of the different materials to produce specimens with dimensions of 10 × 10 × 10 cm³, allowing for the necessary tests to assess the fresh and hardened concrete properties.

Compaction was performed using a vibrating hammer in accordance with the NF EN 12697-32+A1 standard [25], as shown in Fig. 4.

Fig. 4. HILTI vibrating hammer

3.1.2. Mixing and curing process

The specimens were then exposed to temperatures of 20°C, 40°C and 60°C, covered with wet curing, and demolded 24 hours after preparation. They were kept under these conditions until the tests. Afterwards, they were placed in curing environments at their respective temperatures until the performance tests (see Fig. 5).

Fig. 5. Different curing environments

3.2. Testing method

3.2.1. Compressive strength

To assess the CS of the cured RCCP mixtures, 150 cube specimens measuring 10 × 10 × 10 cm were cast and tested at 28, 90 and 180 days. This test was conducted according to the specifications of the American standard EN 12390-3.

3.2.2. Capillary absorption

The water absorption by capillarity in a concrete sample is influenced by factors such as the size, shape, and connectivity of the material's pores [26].

Water displaces air in the pores without external pressure application. To assess this phenomenon, a test is performed by immersing the bottom of the sample in water (see Fig. 6) and measuring the variations in its weight over time. Before the test, the samples are dried at a temperature of 105°C until a stable weight is achieved. The sample sides are then sealed with waterproof resin to prevent lateral absorption. The absorption is measured at regular intervals (0, 4, 9, 16, 25, 36, 49, and 64 minutes) after wiping the surface of the samples with a damp cloth. This procedure follows the guidelines in [27].

Fig. 6. Capillary absorption test

3.2.3. Porosity test

To assess the water-accessible porosity, which helps estimate the volume of pores in a concrete sample, the samples are first saturated under vacuum. After saturation, porosity is calculated by dividing the mass of water in the pores by the apparent volume of the sample, with the latter being determined through hydrostatic weighing. This method follows the guidelines in [28].

To determine the porosity P (%), the specimens are first dried at 105°C for 48 hours and weighed (mass A). They are then immersed in a water bath at 20°C for 24 hours, after which they are weighed again (mass B). The samples are then placed in a 60°C water bath for 5 hours, followed by drying in an oven. After this step, the samples are removed and weighed a third time (mass C). Finally, the hydrostatic weighing test is performed by suspending the specimens on a string from a balance, then immersing them in water at 20°C. The mass is recorded (mass D), as shown in Fig. 7.

$$P(\%) = \frac{C - A}{C - D} \cdot 100\% \quad (1)$$

$$Ap(\%) = \frac{B - A}{A} \cdot 100\% \quad (2)$$

Fig. 7. Hydrostatic weighing of RCCP

3.2.4. Acid and sulfate attack

1) Acid attack

Concrete surfaces are susceptible to both physical and chemical degradation, especially from sulfate and chloride ions, when exposed to aggressive environments. Therefore, it is crucial to assess how resistant these materials are to such attacks. In this study, fifty 100 mm cubic samples were prepared following ASTM C267 standards [20] and cured for 28 days to evaluate the effect of exposure to acidic environments.

To simulate aggressive conditions in the lab, 3% hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) solutions were prepared. Two sets of ten samples from each roller-compacted concrete pavement (RCCP) mix were immersed separately in these acid solutions (HCl and H_2SO_4).

After exposure, a third group of ten samples was tested every 15 days to measure their mass loss. The acid solutions were refreshed every 30 days to maintain a consistent acid concentration throughout the experiment. The samples were exposed for 45 days, after which they were removed from the solutions, rinsed with potable water, and cleaned with a cotton cloth. Their surface-saturated weight was then recorded. Mass loss of samples exposed to acidic environments was calculated using specific equations, which helped evaluate the resistance of the RCCP mixes to these chemical attacks.

2) Sulfate attack

Sulfate attacks can also deteriorate the structure of concrete, especially when exposed to solutions containing sulfate ions, such as sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$). Numerous studies, including those by [22], have examined the effects of these attacks on concrete, mainly focusing on two aspects: the physical degradation of the concrete and quantifying this degradation.

For this study, immersion tests were performed by submerging the samples in sodium sulfate (Na_2SO_4) and magnesium sulfate ($MgSO_4$) solutions, in accordance with the [20]. The RCCP samples were immersed for 45 days in solutions containing 5% Na_2SO_4 and 5% $MgSO_4$. The main goal of this analysis was to assess the effect of adding recycled bituminous concrete waste (RAP) on the concrete's resistance to sulfate attacks.

Chemical tests were conducted on the samples to evaluate their durability and ability to resist sulfate attacks under these specific conditions. The samples were carefully monitored throughout the experiment to better understand how sulfate solutions affected both the mechanical and chemical properties of the concrete, especially those containing recycled materials like RAP. (Fig. 8).

Fig. 8. Acid and sulfate attack test

4. Results and discussion

4.1. Capillary absorption

Figure 9 presents the capillary absorption results of RCCP incorporating with different percentages of RAP at different ages 28, 90 and 180 days, and curing at several temperatures 20°C, 40°C and 60°C. The analysis indicates a relationship between the RAP content, curing temperature and the capillary absorption characteristics of the concrete over time.

At 28 days, capillary absorption decreases with increasing RAP content at all curing temperatures. For example, at 20°C, the capillary absorption for RCCP0 is 14.8, while it decreases to 8.7 for RCCP100. This trend is consistent at 40°C and 60°C, where concretes with higher RAP content exhibit lower absorption. The reduction in capillary absorption at higher RAP levels appears to result from a denser, less porous concrete microstructure.

At 90 days, a noticeable change is observed, especially at higher curing temperatures. At 20°C, capillary absorption significantly decreases with RAP substitution. For RCCP0, it remains relatively high (14), but it drops to 8 for both RCCP50 and RCCP100. This indicates that extended hydration and moderate-temperature curing improve absorption resistance in RAP-containing mixes. A similar trend is evident at 40°C and 60°C, where capillary absorption values are significantly lower than at 28 days, indicating that elevated temperatures and longer curing durations promote improved hydration and increased concrete density.

At 180 days, capillary absorption values stabilise further, with RCCP0 continuing to show relatively higher absorption rates compared to RAP-incorporated mixes. For instance, at 20°C, RCCP0 records an absorption of 13 units, while RCCP100 drops to 7, demonstrating a notable improvement. The same pattern persists at 40°C and 60°C, with RAP-containing mixes consistently exhibiting lower absorption. These results suggest that long-term curing, particularly at elevated temperatures, reduces porosity and enhances concrete density, thereby improving resistance to capillary absorption.

The results demonstrate that increasing RAP content reduces capillary absorption, especially over longer curing periods. This reduction can be attributed to the more compact structure of the concrete as it hydrates over time. Furthermore, higher curing temperatures (40°C and 60°C) seem to further reduce absorption rates, likely due to the enhanced hydration process that occurs at elevated temperatures. This is consistent with findings from other studies, which indicate that the use of RAP in concrete can improve certain durability properties, such as reduced absorption and improved resistance to water penetration [29].

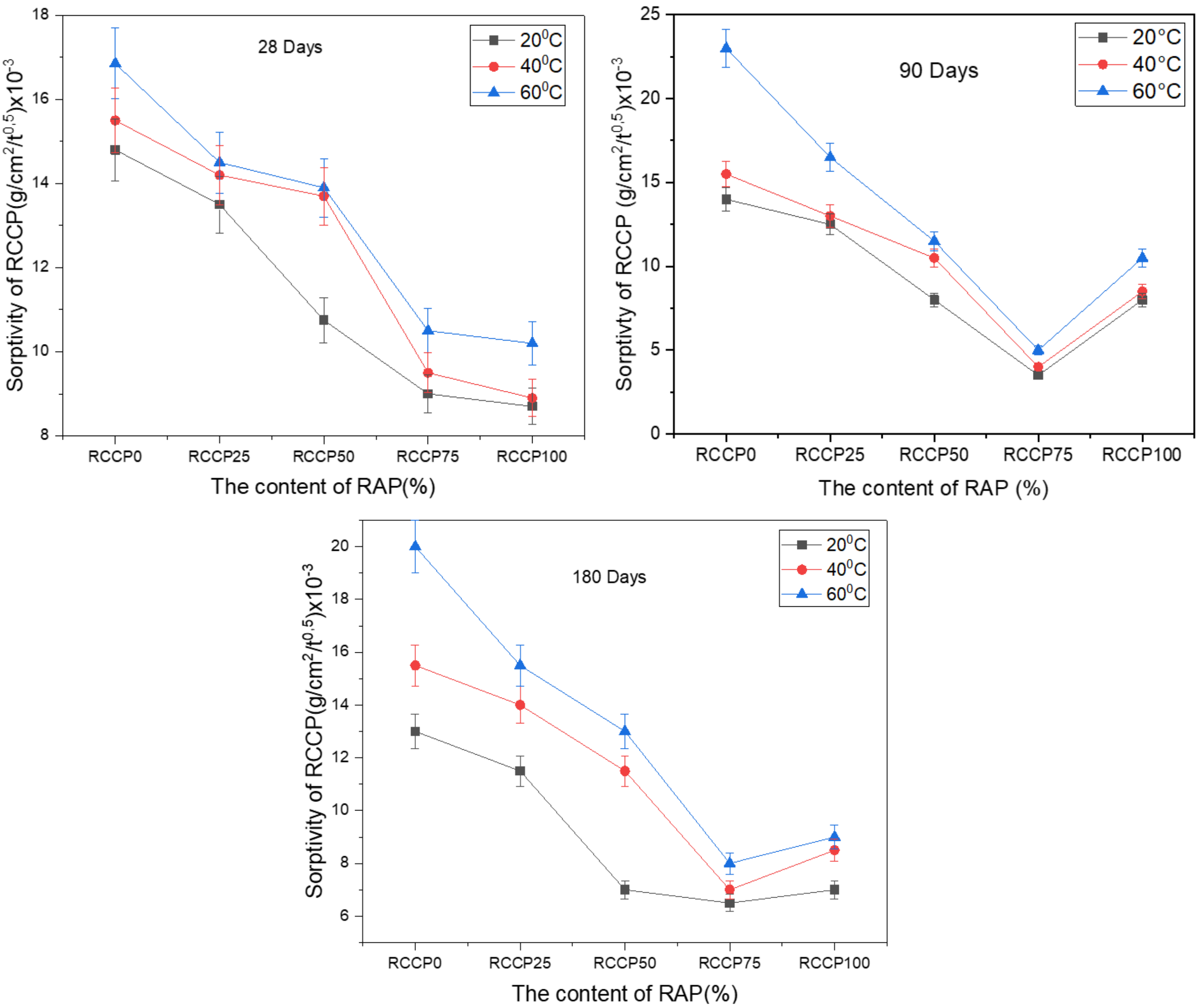

Fig. 9. Sorptivity of RCCPs

4.2. Porosity

Figure 10 provided suggests an analysis of the porosity of roller-compacted concrete (RCCP) incorporating reclaimed asphalt pavement (RAP) at various substitution rates (RCCP0, RCCP25, RCCP50, RCCP75, RCCP100) over different curing times (28, 90 and 180 days) at temperatures of 20°C, 40°C and 60°C. The results indicate that increased RAP content reduces concrete porosity, resulting in a dense material.

At 28 and 90 days, the porosity remains relatively similar across the different temperatures. At 20°C, the porosity decreases as the RAP content increases, with RCCP0 having the lowest porosity of 12.1% and RCCP100 having the highest of 8.3%. This trend is consistent at 40°C and 60°C, where the porosity is slightly reduced at higher RAP substitution rates. The data suggest that while RAP is an aggregate that may contain voids, it also influences concrete hydration, contributing to an overall increase in porosity compared to the RCCP.

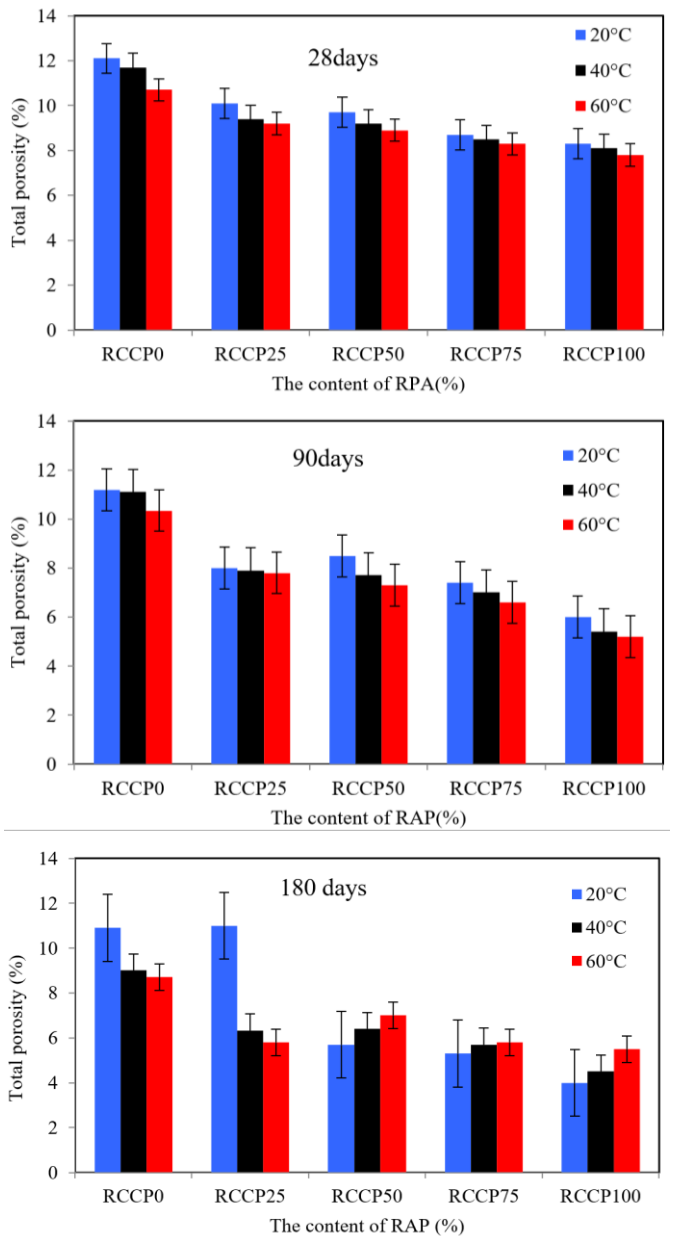

Fig. 10. Porosity of RCCPs

At 180 days, the porosity shows a marked difference compared to earlier times. For example, at 20°C, RCCP0 had a porosity of 10.9%, while RCCP100 showed a significant decrease in porosity, indicating that the RAP content significantly affects the long-term density of the concrete. The porosity reduction at 40°C and 60°C in high-RAP mixes may be attributed to the higher curing temperatures that promote more hydration and potentially a more compact microstructure, thus reducing the porosity in certain mixes, particularly for the RCCP0 and RCCP25 mixtures.

Overall, the results suggest that while increasing RAP content leads to higher porosity in the initial curing stages, at later curing ages (180 days), the RAP-containing mixes can achieve comparable or even better porosity levels, likely due to the continued hydration of the cement and the effects of the higher temperatures on the cement paste. This indicates that RAP can influence the durability and performance of concrete; however, the effects depend on the curing temperature, and higher RAP substitution may still result in desirable porosity and strength after extended curing periods. The observed trends align with existing research on the influence of RAP on the properties of concrete, where higher RAP content generally increases porosity, but long-term performance can still be achieved with proper mix designs and curing conditions [12]. These are the same results found by Modarres et al. [5].

4.3. Water absorption

The water absorption results for different periods (28 days, 90 days, 180 days), based on the percentage of Reclaimed Asphalt Pavement (RAP) substitution (0%, 25%, 50%, 75%, 100%) and various curing temperatures (20°C, 40°C and 60°C), show interesting trends.

At 28 days, the results show a trend where water absorption decreases as the percentage of RAP increases in the concrete. For example, at 20°C, the concrete without RAP (RCCP0) has a water absorption of 5.4%, while mixtures with higher percentages of RAP show lower absorption values, reaching 3.6% for RCCP100. This may be attributed to concrete matrix densification due to the substitution of natural aggregates with RAP, reducing the porous spaces and thus limiting the amount of water the concrete can absorb [30].

At 90 days, the results show that water absorption remains relatively stable for samples with low percentages of RAP (25%, 50%), while mixtures with 75% and 100% RAP show significant reductions in absorption. This appears related to the progression of hydration reactions over time and the filling effect of RAP, which contributes to a more compact and less permeable concrete structure. At 60°C, the results show greater reductions in absorption, suggesting that higher temperatures promote better RAP reactivity and, consequently, better densification of the concrete matrix [31].

At 180 days, the trends observed at 28 and 90 days persist, but with more pronounced differences. Concrete samples with higher RAP percentages (particularly RCCP75 and RCCP100) show increasingly lower water absorption. This indicates that the effect of RAP on reducing water absorption becomes more significant over time, likely due to the completion of hardening processes and the formation of secondary products that reduce porosity [32].

Long-term results suggest that partial substitution of natural aggregates with RAP can improve the water absorption resistance of concrete, especially as curing time and temperatures increase. This can enhance the durability of concrete by making it less permeable and more resistant to water infiltration, an important factor for structures exposed to humid environments or freeze-thaw conditions [33].

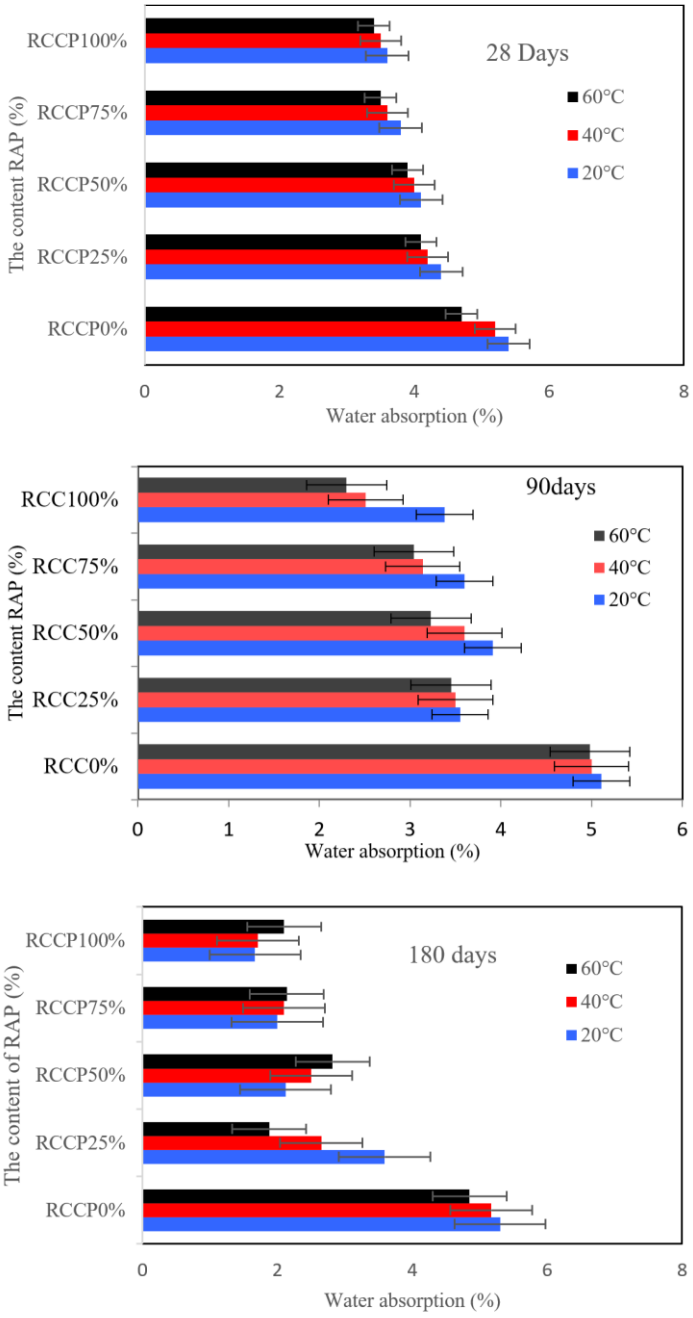

Fig. 11. Water absorption of RCCPs

4.4. Correlation between porosity and water absorption

The correlation between porosity and water absorption in concrete made with recycled aggregates, such as concrete waste or recycled asphalt aggregates (RAP), shows that as porosity increases, water absorption also increases. The results indicate that the addition of RAP in concrete leads to an increase in porosity, as this material may contain porous areas and irregularities, thus increasing the voids in the concrete matrix. This results in a greater water absorption capacity, particularly for mixes with higher percentages of RAP. For example, samples with 100% RAP showed higher absorption rates than those made with natural aggregates, confirming the relationship between porosity and water absorption [34].

The effect of curing time and temperature was also observed. At higher curing temperatures (40°C and 60°C), the hardening reactions reduce porosity and, consequently, water absorption. This phenomenon is more pronounced in concrete samples cured at high temperatures, suggesting that heat promotes cement reactivity, thus reducing porosity and water absorption. As a result, samples with more than 50% RAP showed a reduction in water absorption over time, particularly after 90 and 180 days of curing, indicating that porosity decreases over time.

In terms of durability, lower porosity, which leads to lower water absorption, is associated with better resistance to chemical and physical attacks. While mixes with higher percentages of RAP initially showed higher water absorption due to their greater porosity, extended curing at higher temperatures allowed for densification of the matrix, thus reducing water absorption and improving the durability of the concrete. These results suggest that managing porosity is crucial for producing durable concrete, especially in humid or aggressive environments (Fig. 12).

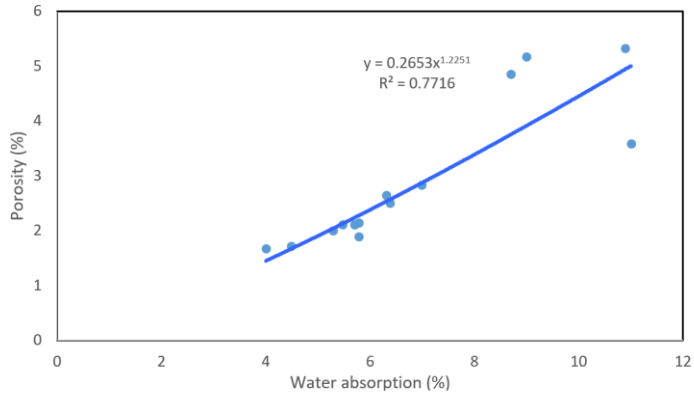

Fig. 12. Correlation between porosity and water absorption at 180 days

5. Durability tests

5.1. Sulfate and acid attacks

Figure 13 illustrates the mass loss of RCCPs immersed in 5% Na_2SO_4 and $MgSO_4$ solutions. The addition of 25%, 50%, 75%, and 100% of RAP results in a mass gain after 220 days of immersion in a $MgSO_4$ solution, compared to the control concrete (RCCP0), as shown in Fig. 13. In contrast, the mass loss of concrete samples immersed in the Na_2SO_4 solution increases by approximately 65%. A greater expansion is observed in the concretes exposed to the $MgSO_4$ solution than to the Na_2SO_4 solution. This mass loss in RCCP specimens may be attributed to interconnected porosity in the cement matrix, allowing sulfate ions to penetrate and leach calcium sulfate into the acidic solutions [16-35].

The results show that the mass gain steadily increases with immersion time up to 15 days. After this period, a continuous increase in mass is observed with age. This is due to the formation of expansive mineral phases (such as gypsum and secondary ettringite), which can swell and crack the cement paste. When crystal growth within pores becomes spatially constrained, a crystallization pressure forms, causing expansion and eventually cracking the surface of the concrete. Sulfate attack results from a chemical reaction between the sulfate ions in the water and calcium aluminate (C_3A) in the cement paste, producing calcium sulfate hydrate.

The control concrete (RCCP0) shows the lowest mass gains compared to concretes containing 25%, 50%, 75%, and 100% RAP content. The RCCP100 concrete shows a higher mass gain than the other RCCP mixtures. It was also observed that the mass loss for RCCP50 concrete is 50% lower than that of RCCP100 in most aggressive environments.

This study suggests that replacing 50% of the coarse aggregates with RAP in RCCP mixtures could be beneficial for producing concrete used in sidewalk construction in aggressive environments rich in sulfate and chloride ions. Moreover, the results support the use of the coarse fraction of RAP for the construction of RCCP pavements in areas near sulfate sources. Indeed, the RCCP 25 and RCCP50 mixtures experienced only 4% and 2% additional mass loss, respectively, compared to the control mix when subjected to sulfate attack.

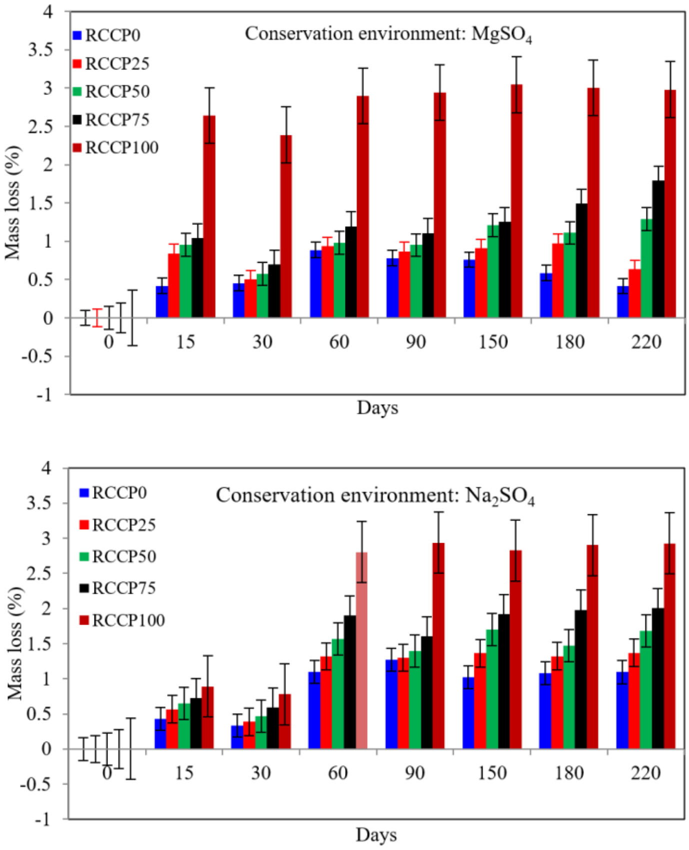

Fig. 13. The mass loss of (RCCP) immersed in both $MgSO_4$ and Na_2SO_4

5.2. Compressive strength

The presented results concern the CS of roller-compacted concrete, depending on different percentages of substitution of RAP (Construction and Demolition Waste) over a period ranging from 0 to 220 days.

The CS values show a trend of increasing over time. Indeed, measurements taken at 60 and 90 days reveal peaks in strength, followed by a slight decrease or stabilisation of values thereafter. This indicates that the concrete reaches a certain level of strength over time, but this strength may stabilise or even slightly decrease after a certain point.

Analysing the results based on substitution percentages reveals significant differences. At 0% substitution, the Cs values are the highest, reaching up to 28.03 MPa at 220 days.

This suggests that the absence of substitution allows for optimal concrete strength. At 25% substitution, the Cs values decrease slightly, with a maximum of 27.15 MPa. Although the strength is still relatively high, it begins to show the impact of incorporating waste. At 50% substitution, the strength continues to decrease, reaching a maximum of 23.8 MPa, indicating that increasing substitution has a negative effect on CS. At 75% substitution, the values drop significantly, with a maximum of 19.94 MPa, and at 100% substitution, the results show the lowest values, peaking at 13 MPa. This highlights that the exclusive use of RAP waste severely compromises the strength of the concrete.

The results also show a rapid increase in strength in the early days (0 to 30 days), followed by a slowdown in growth. After 90 days, the strength appears to stabilise or slightly decrease, which may indicate that the concrete reaches a plateau in its strength. This behaviour is typical of cementitious materials, where most of the strength gain occurs in the first few weeks.

It is important to note that there is significant variability in the results, especially at higher substitution percentages (75% and 100%). This variability may indicate increased sensitivity to the quality of the materials used or the compaction method applied, emphasising the importance of controlling manufacturing conditions to ensure optimal performance.

In summary, the use of RAP waste in roller-compacted concrete appears to have a negative impact on CS, particularly at higher substitution levels. The results suggest it is preferable to limit substitution to lower levels to maintain adequate strength. Further studies may be necessary to optimise formulations and compaction methods to improve the performance of concrete containing waste substitutions.

5.3. Weight loss

Figure 14 represents the mass loss of roller-compacted concrete pavement (RCCP) with varying percentages of reclaimed asphalt pavement (RAP) substitution (0%, 25%, 50%, 75%, and 100%) when immersed in both HCl (hydrochloric acid) and H_2SO_4 (sulfuric acid) solutions over a period of 0 to 220 days. These results are essential for assessing the concrete's resistance to acidic environments, which can significantly degrade concrete structures.

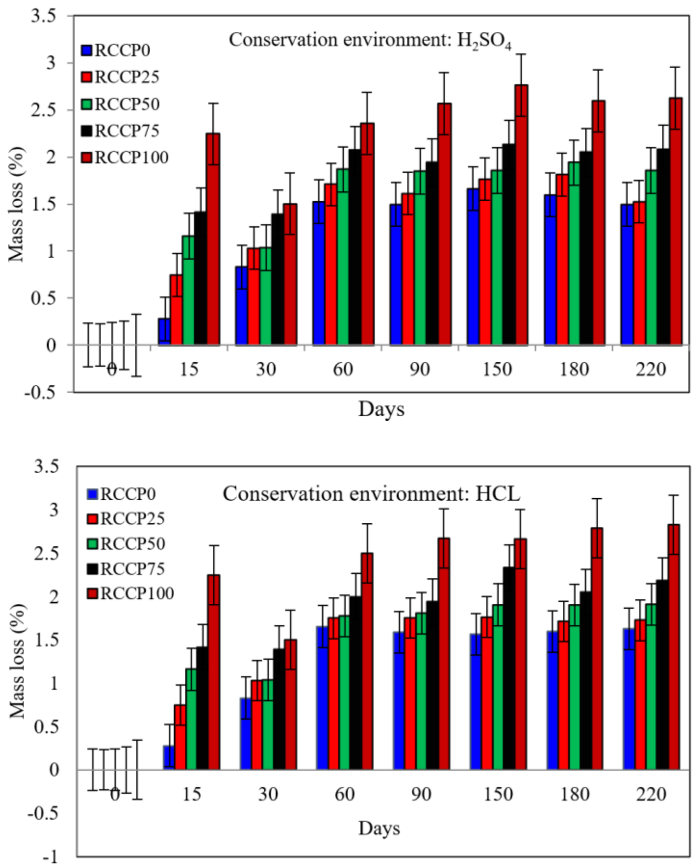

Fig. 14. Comparison of measured and calculated weight loss mortars immersed in H_2SO_4 and HCL solutions

For the HCl exposure, the control mix (0% RAP substitution) shows an increase in mass loss over time, reaching a value of 1.62% after 220 days. The mass loss increases more rapidly in the initial period (from 15 to 60 days) before levelling off. With the increase in RAP content, the mass loss becomes more pronounced. For example, the mix with 100% RAP substitution exhibits a mass loss of 2.83%, which is nearly double the mass loss observed for the control mix. This suggests that higher RAP content accelerates degradation in acidic environments, likely due to the increased porosity and permeability associated with RAP. The presence of RAP, which contains bitumen, may lead to enhanced water and acid penetration, accelerating the deterioration process [35].

The behaviour observed in the H_2SO_4 (sulphuric acid) exposure is quite similar. The control mix (0% RAP) again shows a steady increase in mass loss, reaching a value of 1.49% after 220 days. The mass loss is more significant in the early stages (15 to 60 days), after which it stabilises somewhat. As the RAP content increases, the mass loss also increases. For instance, the 100% RAP mix shows a mass loss of 2.63% after 220 days. This indicates that, similar to the HCl exposure, higher RAP content results in greater degradation due to the acid's aggressive attack on the concrete matrix. This trend may be explained by the formation of expansive products like gypsum and secondary ettringite from sulfuric acid reactions, as they generate internal pressures that lead to cracking and further deterioration [36].

Both HCl and H_2SO_4 expose the concrete to aggressive chemical reactions that degrade the material over time. The increased mass loss with higher RAP content suggests that the material's porosity plays a significant role in its resistance to acidic attack. The higher the RAP content, the more vulnerable the concrete becomes to both hydrochloric and sulphuric acid exposure due to the enhanced permeability of the concrete, which allows for greater acid penetration [37].

These findings align with previous research indicating that the use of RAP in concrete can lead to reduced durability, particularly when exposed to acidic environments. Studies have shown that RAP, while environmentally beneficial, can negatively affect the long-term performance of concrete due to its high porosity and the chemical composition of the asphalt binder, which may influence the overall durability of concrete in aggressive environments [38].

The results presented in Fig. 14 reflect the mass loss in roller-compacted concrete (RCCP) with varying percentages of reclaimed asphalt pavement (RAP) substitution (0%, 25%, 50%, 75%, and 100%) after immersion in Na_2SO_4 (sodium sulfate) and $MgSO_4$ (magnesium sulfate) solutions over a period of 0 to 220 days. These tests assess the concrete's resistance to sulfate attack, a crucial consideration in environments rich in sulfate ions, which can accelerate the deterioration of concrete structures.

For the Na_2SO_4 (sodium sulfate) exposure, the control mix (0% RAP substitution) shows a gradual increase in mass loss over time, reaching about 1.09% after 220 days. The mass loss is more pronounced in the early stages (between 15 and 30 days) and tends to stabilise as time progresses, likely due to the formation of expansive compounds like ettringite. However, as the percentage of RAP in the mix increases, the mass loss also increases. For instance, the concrete with 25% RAP shows a mass loss of 1.37% after 220 days, while the mix with 100% RAP reaches a mass loss of 2.93%. This indicates that the concrete with a higher RAP content is more susceptible to sulfate attack. The increased permeability of the concrete, due to the porous nature of RAP, allows sulfate ions to penetrate the matrix more easily, accelerating the chemical reactions that lead to the formation of expansive products [31].

In the case of $MgSO_4$ (magnesium sulfate), the mass loss is generally more significant compared to sodium sulfate exposure, with the 100% RAP mix exhibiting a substantial increase in mass loss over the duration of the test. This is primarily due to the aggressive chemical reactions between magnesium sulfate and the calcium aluminates in the cement paste, which produce expansive minerals like gypsum and secondary ettringite. These reactions generate internal pressures that lead to cracking and further degradation of the concrete [39] for the control mix, the mass loss after 220 days is around 0.42%, while for the 100% RAP mix, the mass loss increases to 3.00%. This suggests that concrete containing RAP is more vulnerable to degradation when exposed to magnesium sulfate. The higher porosity and inherent variability of RAP contribute to this higher vulnerability, as sulfate ions penetrate more easily and induce greater damage [40].

Increasing mass loss with higher RAP substitution indicates greater susceptibility to sulfate-induced deterioration as the percentage of RAP increases. This behaviour is consistent with previous studies that have shown that the use of reclaimed asphalt pavement can alter the porosity and chemical composition of the concrete, making it more susceptible to chemical attack, particularly in sulfate-rich environments [12]. The porous nature of RAP allows for greater ion penetration, which in turn enhances the rate of sulfate attack and the associated expansion and cracking in the concrete matrix.

Despite the environmental benefits of using RAP in concrete mixtures, these results highlight the need to optimise the amount of RAP used in sulfate-exposed environments. Measures such as reducing the RAP content or incorporating supplementary cementitious materials (SCMs) like fly ash, slag, or silica fume can be effective in improving sulfate resistance. These additives help to reduce the porosity of the concrete, improve the microstructure, and mitigate the expansive reactions that contribute to mass loss and degradation [41] Furthermore, detailed characterisation of RAP chemical composition and properties could help identify the best mix design strategies to enhance the durability of concrete structures in sulfate-rich environments.

5.4. Prediction of CS based on mass loss in RCCP

Several researchers have indicated that there exists a relationship between the mechanical strength and the durability performance of the cement. Debbarma et al., 2021; Nandi & Ransinchung, 2023 [17,30] have found an important correlation between the weight loss and CS in RCCP mixes with high RAP content exhibit significantly higher mass loss after prolonged exposure to acidic solutions.

This loss is closely linked to the decline in CS, sometimes reaching up to 40–50% reduction after 180 to 360 days of immersion in sulfuric acid.

Predicting SC of RCCP in aggressive environments is an important consideration for civil engineering practitioners, as it allows us to understand the behaviour of concrete under sulfate and acid attacks. For this reason, the development of an estimation method for the Sc of RCCP immersed in sulfate and acid solutions at various ages is essential.

Following experimental data calibration, an exponential model was developed to predict CS as a function of the weight loss of RCCP, considering the RAP content and the type of solution (acid or sulfate). The proposed CS estimation can be written as follows:

$$S_c(t,\%RAP) = a.e^{-0.3\times W(t,\%RAP)} + b \quad (3)$$

where W (%) is the weight loss index, SC is the compressive strength at t (days). The coefficients a and b are obtained by the adjustment of the experimental results of the concrete studied.

The values of the parameters of Eq. (3) are presented in Tab. 3.

Table 3. Values of parameters of the Eq. (3) for different solutions

	a	b	R^2	Error deviation (%)
Sodium sulfate	43.4	0.6	0.94	3
Magnesium sulfate	32.8	0.54	0.94	4
Sulfuric acid	81.1	2.58	0.897	6
Hydrochloric acid	78.2	2.40	0.913	5

5.5. Comparison and validation of the equation proposed

Figure 15 shows the comparison between the measured and calculated results using the proposed prediction Eq. (3) for several mixtures studied, in which a perfect alignment with a satisfactory correlation coefficient is obtained. The correlation coefficients close to the unit and the error deviation less than 6% as shown in Tab. 3, indicate that the proposed equation can accurately predict the compressive strength according to the weight loss for different types of concrete immersed in different sulfate and acid solutions.

To validate the proposed equation, three experimental results available in the literature are used [42-44]. Table 4 shows the comparison results of Sc between the measured and calculated results using the proposed prediction Eq. (3) for several mixtures studied, in which a perfect alignment with a satisfactory correlation coefficient is obtained. The correlation coefficients close to the unit and the error deviation less than 6% as shown in Tab. 4, indicate that the proposed equation (3) can accurately predict the compressive strength according to the weight loss for different types of RCCP immersed in different sulfate and acid solutions.

Table 4. Comparison of Sc measured and calculated by Eq. (3) for three sets of data

Ref.	Solution	Equation of correlation	R^2	Error deviation (%)
[42]	H_2SO_4	Sc(m) = 0.795× Sc(cal)	0.91	4
[42]	HCL	Sc(m) = 0.85× Sc(cal)	0.93	3
[43]	H_2SO_4	Sc(m) = 0.90× Sc(cal)	0.94	2
[44]	HCL	Sc(m) = 0.71× Sc(cal)	0.88	5
[44]	H_2SO_4	Sc(m) = 0.79× Sc(cal)	0.85	6

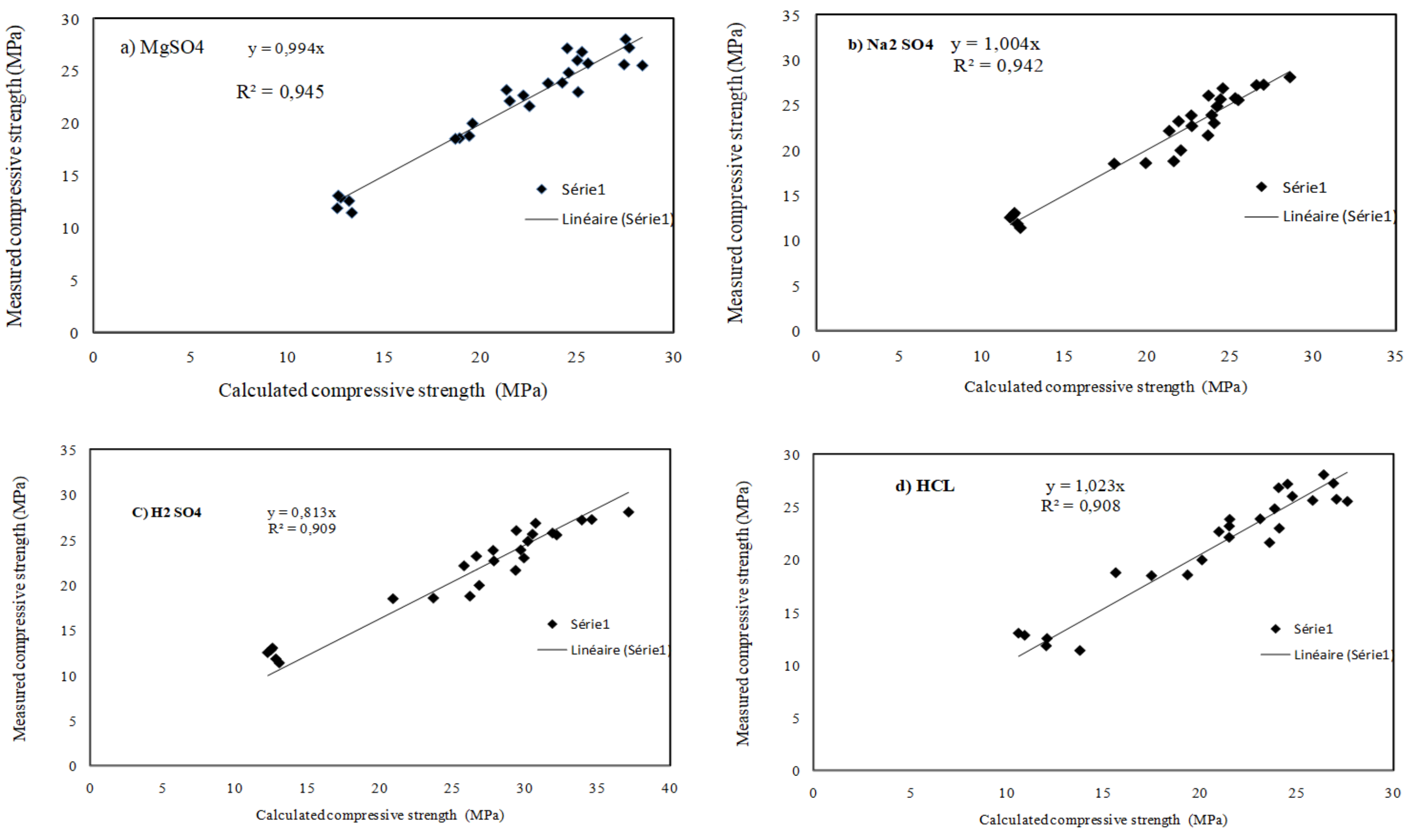

Fig. 15. Comparison of measured and calculated compressive strength for concrete immersed in different types of solution

6. Conclusion

Using Recycled Asphalt Pavement (RAP) in Roller Compacted Concrete Pavement (RCCP) significantly affects various properties, and its impact can be both beneficial and challenging depending on the RAP content and curing conditions.

- RAP incorporation increases porosity in RCCP, primarily due to the inherent voids in the recycled aggregates. As the RAP content increases, porosity tends to rise, which in turn results in higher water absorption. This increase in water absorption is due to the more porous structure created by the RAP, which facilitates the penetration of water. However, these negative effects can be mitigated with proper curing conditions, particularly at elevated temperatures (40°C and 60°C). Enhanced hydration during curing reduces porosity and water absorption over time, demonstrating that with optimal curing, the impact of RAP on porosity and water absorption can be controlled.

- Incorporating RAP into RCCP generally leads to a decrease in CS, particularly as the RAP content increases. This reduction is attributed to the higher porosity and increased water absorption associated with the use of RAP. Higher RAP content results in a more porous matrix, which weakens the concrete. However, RCCP with lower RAP content (such as 25%) can maintain relatively higher CS compared to mixes with higher RAP percentages. This suggests that while RAP can affect the CS of RCCP, careful mix design and curing strategies can help maintain satisfactory performance.
- The resistance of RCCP containing RAP to chemical attacks, such as sulfate (Na_2SO_4) and acid (HCl and H_2SO_4) attacks, is lower compared to conventional RCCP. This is due to the increased porosity, which allows aggressive ions to penetrate more easily. However, mixes with lower RAP content (like 25%) perform better than those with higher RAP content, indicating that some degree of RAP substitution can still yield acceptable chemical resistance. Proper curing and mix optimisation can further improve the performance of RAP-based RCCP in aggressive environments.
- The net effect of RAP on RCCP behaviour represents a trade-off between the environmental benefits of using recycled materials and the potential reduction in material properties such as strength and resistance to chemical attacks. However, with proper curing techniques, especially at elevated temperatures, the negative impacts of RAP on the mechanical properties and durability of RCCP can be mitigated. Additionally, RAP provides a sustainable solution by reducing the need for virgin aggregates, contributing to more eco-friendly construction practices.

Conflict of interest

The authors declare that they have no conflict of interest.

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