Exploring the use of recycled coarse aggregates from different sources in Self-Compacting Concrete for sustainable building

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RESUME The construction industry depends heavily on Natural Aggregates (NA), leading to major environmental and economic issues due to extraction costs and resource loss. Recycled coarse aggregates (RCAs) from Non-Harmful Construction and Demolition Waste (NHCDW) are the best alternative for Self-Compacting Concrete (SCC). This study looks at the performance of SCC using different types of recycled gravels from NHCDW, such as concrete, bricks, bitumen, roof tiles, and plastics (PVC). The fresh and hardened states of SCC were analyzed, with measurements taken for workability, porosity, density, and mechanical strength. The findings indicated that the substitution of recycled gravels resulted in adequate performance, except when 85% of recycled brick gravel was replaced with natural gravel. However, a slight decrease in mechanical strength was observed for all mixes. The results indicated that SCC with up to 85% recycled concrete coarse aggregates maintained satisfactory rheological and mechanical properties. However, replacing 85% natural gravels with recycled bricks gravels led to an 18.5% reduction in mechanical properties compared to the reference, failing to meet the requirement. In general, the mechanical strengths, including compressive, and tensile strength decreased by 8.8% to 18.5% and 9.2% to 14.8 % respectively, compared to the reference.

These findings provide valuable insights into the limited values of coarse aggregates from NHCDW materials for concrete purposes. This study is part of the work in the European project 101091679-MOBICCON-PRO (MOBile and Innovative Circularity for Construction Products) framework-Horizon-Cl4-2022-Twin-Transition-01. This research aids sustainable construction by providing guidelines for using RCA in concrete, which lowers environmental impact and supports the circular economy.

Mots-clefs Recycled coarse aggregate, Self-compacting concrete, Construction and demolition waste, Sustainability, Mechanical properties of concrete.

I. INTRODUCTION

In an era marked by rapid urbanization and growing environmental issues, the construction industry stands at the forefront of global resource consumption. The reliance on natural aggregates (NA) for construction activities has led to significant environmental degradation and economic challenges, necessitating innovative solutions to promote sustainability. One promising option is the utilization of recycled gravels derived from NHCDW. This approach not only reduces the strain on natural resources but also aligns with the principles of the circular economy, promoting a more sustainable future. In the current era, the construction industry extensively utilizes concrete as a primary construction material (Kumar Sharma, 2021). Factors such as population growth, ongoing industrial expansion, infrastructure projects, and residential construction generate substantial amounts of CDW, underscoring the need for improved recycling methods (Kabirifar et al., 2020;

Lee et al., 2024). Reusing construction and demolition waste as recycled coarse and fine aggregates minimizes the consumption of natural resources, reduces landfill usage, and promotes sustainable construction practices (Ibrahim et al., 2023; Luciano et al., 2022).

In many European countries, there is a growing trend to treat waste as a resource that can be reused in various ways. Construction waste accounts for nearly 38% of the total waste generated by economic and household activities across the European Union (Eurostat. Statistics Explained., 2025; Teixeira et al., 2023).

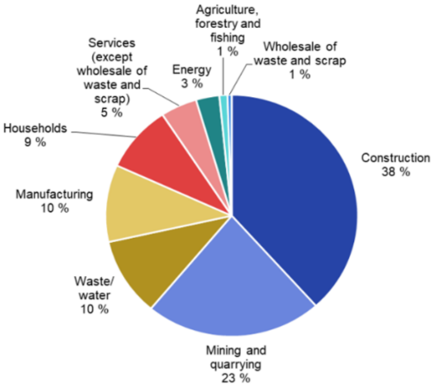

FIGURE 1. Waste generation by economic sectors and households in the EU, 2022 (% of total waste) (Eurostat. Statistics Explained., 2025)

Recycled gravels derived from NHCDW can be classified into coarse and fine categories based on particle size (Luciano et al., 2022). Fine recycled concrete aggregates (FRCA), which are smaller than 4 mm, are produced by crushing cement-based concrete. These aggregates consist of natural aggregates coated with hardened cement paste. In contrast, coarse aggregates derived from NHCDW have a particle size ranging from 4 to 8 mm (Sbardelotto et al., 2024). Common materials found in recycled CDW include concrete, bricks, roof tiles, wall tiles, PVC, and bituminous materials (Almtori & Al Hassan, 2024; Luciano et al., 2022; Sbardelotto et al., 2024).

Research has shown varying effects of using recycled gravels in concrete. Several studies have observed that incorporating recycled gravels up to 25% of the total gravel content has a minimal impact on the compressive strength of recycled concrete (Dang et al., 2024; Medina et al., 2014; Pimentel et al., 2020). However, other investigations highlight potential drawbacks as the percentage of recycled gravels increases. One study demonstrated that as the proportion of recycled gravels increased, the splitting tensile strength of concrete decreased (Busari, 2022) .

This study explores the potential of incorporating recycled gravels into SCC, a concrete known for its superior workability and mechanical properties. By examining the performance of SCC with various types of recycled gravels, including concrete, bricks, bitumen, roof tiles, and plastics (PVC), we aimed to uncover the feasibility and limitations of this sustainable alternative. The research evaluates both the fresh and hardened states of SCC, focusing on critical parameters such as workability, porosity, density, and mechanical strength.

II. EXPERIMENTAL METHODOLOGY AND MATERIALS

As part of this study, the methodology outlined in Figure 2 illustrates our comprehensive approach to investigating the optimal utilization of waste materials, with a particular focus on coarse aggregates.

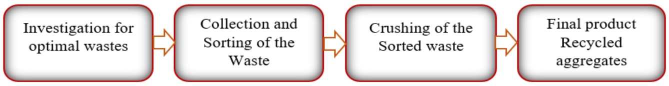

FIGURE 2. **Recycled coarse aggregates optimization from CDW**

In this study, SCC was formulated using recycled gravels sourced from NHCDW, following the specified guidelines in (NF EN 12350-9, 2010), (NF EN 12350-8, 2019),(NF EN 12350-12, 2010),(NF EN 12350-10, 2010). To achieve optimal performance, rheological properties, and workability were tested. Specific raw materials were carefully selected. These materials are detailed in Table 1, which provides a comprehensive overview of their specifications and roles in the SCC mixture.

TABLE 1. **Raw materials and specifications for SCC Mix**

Material Name	Specification
Cement	CEM I 52.5 N (EQIOM, France)
Fillers	BETOCARB HP-EC
Admixture	DYNAMON NRG 1031

In this study, the cement utilized has a compressive strength of 50 MPa. To mitigate issues such as bleeding and segregation, limestone fillers were integrated into the SCC. Furthermore, a superplasticizer was added to enhance the workability and overall performance of the SCC, particularly when using recycled gravels, ensuring improved flow and consistency.

The study considers three primary sources of NHCDW:

1. CDW generated from the demolition of buildings (reinforced concrete and masonry bearing structures);
2. CDW generated from reinforced concrete facilities.
3. CDW generated from the rehabilitation of buildings.

It is assumed that a general pre-demolition audit has been conducted and that some hazardous CDW components (such as asbestos-containing materials) have been removed.

One main type of recycled material is considered:

- Recycled gravels for concrete

Table 2 presents the recycled gravels and their related sizes used in this study.

TABLE 2. **Specification of gravels for SCC Mix**

Types of gravels	Coarse Aggregates	Designation	Size (mm)
Natural aggregates	NA		4/10
Recycled coarse aggregates	Bricks	Rb	4/10
	Ceramic Tiles (walls/floor)	Rb2/Rb3	
	Roof Tiles	Rb1	
	Bituminous	Ra	
	Concrete	Rc	
	Plastics	Rx	

The crushed recycled gravels underwent physical testing such as porosity, water absorption, and apparent density to evaluate their suitability applications (Table 3).

TABLE 3. Physical properties of the recycled gravels

Materials	Properties		
	Water absorption (%)	Porosity (%)	Apparent density (kg/m^3)
Natural gravel (GN)	0.81 ± 0.17	0.56 ± 0.11	2680 ± 13.24
Recycled bricks gravel (Rb)	10.13 ± 0.60	7.28 ± 0.46	2200± 5.24
Recycled roof tiles gravel (Rb1)	7.68 ± 0.10	5.56 ± 0.06	2050± 8.84
ycled concrete gravel (Rc)	8.16 ± 0.30	5.87 ± 0.23	2250± 7.02
Recycled floor/wall tiles gravel (Rb2)	1.96 ± 0.53	1.49 ± 0.36	2160± 11.05
Recycled bitumen gravel (Ra)	1.22 ± 0.27	1.02 ± 0.20	1270± 6.03
Recycled PVC gravel (Rx)	1.12 ± 0.10	0.47 ± 0.02	1250± 9.17
Natural sand (Sn)	1.19 ± 0.43	0.81 ± 0.18	2670± 6.39

B. Mix design for SCC

The mix design was elaborated to achieve the targets of a resistance class of C35/40, an XC4 class of environment exposure, and a consistency class of SF2 (650 – 750 mm slump flow) and VF2 (> 9 sec). We adopted a minimum cement dosage of C_{min}=300 kg/m^3 to attain a resistance class of C35/40. The limit values for the composition and properties of concrete depend on the exposure class (XC), according to Table NA.F.1 of standard EN 206-1/CN, are implied. Table 4 shows the SCC designation and mix formulation with the constituent (kg/m^3).

TABLE 4. SCC Mix Design ($in\ kg/m^3$). for Six Mixes with Different Recycled Coarse Aggregates

ID	Mixes	Cement	Filler	SP	Water	NFA	NCA	Rc	Rb	Rb1	Rb2	Ra	Rx
Ref	Reference	300	250	7.2	182	894	716	X	X	X	X	X	X
M1	85%Rc_15%Rb2	300	250	7.2	182	894	X	507	X	87	X	X	X
M2	40%Rc_15%(Rb1_Rb2_Ra_Rx)	300	250	7.2	182	894	X	238	X	81	87	50	50
M3	50%Rc_50%Rb	300	250	7.2	182	894	X	298	292	X	X	X	X
M4	85%Rb_15%Rc	300	250	7.2	182	894	X	89	496	X	X	X	X
M5	40%Rb_15%(Rc_Rb2_Ra_Rx)	300	250	7.2	182	894	X	89	233	X	87	50	50

III. RESULT AND DISCUSSION

A. Fresh state properties of SCC

The rheological properties of the mixtures are illustrated in Figure 3a. The slump flow range varies from 688 mm to 725 mm, corresponding to a consistency class SF2 (650 mm ≤ SF ≤ 750 mm). Substituting 85% of natural gravels with crushed recycled gravels appears to decrease the slump flow. This is due to the higher water absorption and rougher texture of recycled gravels compared to natural gravels (Sasanipour and Aslani, 2020), (Guessoum et al., 2023), (Kapoor et al., 2020). In this study, all formulations achieve the target consistency class SF2 (NF EN 12350-8). Introducing Rb with Rc slightly reduces the flow capacity in an unconfined environment. These findings align with previous literature results (Señas et al., 2016). Moreover, the viscosity of the SCC mixes, measured by T_{500}, showed that replacing natural gravel with recycled gravels increases T_{500}, thereby reducing workability. As previously indicated, the higher water absorption of recycled gravels results in less free water in the mix, increasing viscosity and decreasing concrete flowability. During mixing, old mortar bonded to the gravels may decompose, increasing the fine content and further altering the flow characteristics (Kebaïli et al., 2015), (González-Taboada et al., 2017), (Güneyisi et al., 2014). It is important to highlight that all formulations exhibit a viscosity within the acceptable range for T_{500}, which is higher than 2 seconds. The evolution of the flow time measured through the V-Funnel (sec) and the corresponding values obtained at T_{500} are presented in Figure 3b. A clear correlation can be established based on the present work and literature (Equation 1), (Sheen et al., 2021), (Mohamad et al., 2016), (Mishra and Panda, 2020),(Hilal et al., 2021) (Kumar Sharma, 2021),(Kapoor et al., 2020), (Rizwan et al., 2022), (Rashwan et al., 2022), (Mousavi Alizadeh et al., 2021), (Revathi et al., 2013), and (George and Anil, 2018).

$$V_{Funnel}(S) = 5.08\, T_{500}^{0.42} \qquad \text{With } R^2 = 0.707 \qquad (1)$$

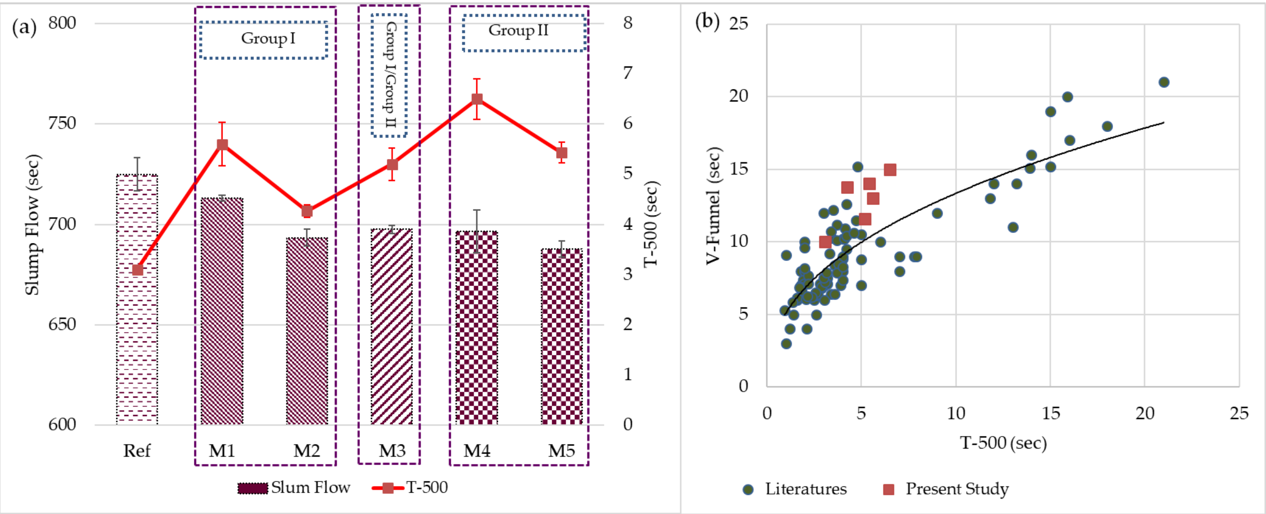

FIGURE 3. a) **Spreading with the different mixes b) Correlation between t500 and V-Funnel flow time**

The L-box (H2/H1) and J-Ring (PJ) tests were conducted to assess the workability and passing ability of SCC in reinforced conditions. The obtained results are illustrated in Figure 4. All H2/H1 ratios fall within the recommended range of 0.8 to 1.0, while the PJ values are ≥ 10 mm, in accordance with established standards. (NF EN 12350-10, 2010),(NF EN 12350-12, 2010).

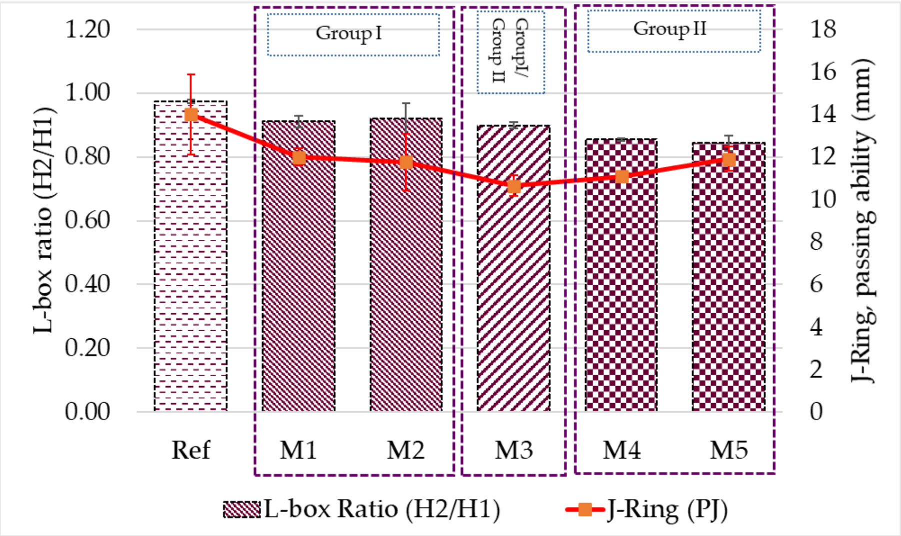

FIGURE 4. **Filling capacity of SCC with reinforcing bars**

Figure 5 presents the fresh state of the SCC, demonstrating excellent stability with no visible signs of bleeding or segregation. This ensures uniform consistency and homogeneity throughout the mixture.

FIGURE 5. **Workability, flowability, and passing ability of SCC**

B. Physical properties of SCC

The experimental results in Figure 6 illustrate the porosity “n (%)” evaluated at 28 days using the vacuum method. The data indicate that the porosity of concrete containing recycled gravels is higher compared to the reference mixture. This increase can be attributed to the inherently higher porosity of the recycled gravels, as previously established by Omary et al., 2016. The decrease is more significant for SCC predominantly using recycled brick gravel (Group II) than for recycled concrete gravel (Group I) due to the more porose behavior of the Rb. The findings obtained at 28 days suggest that the SCC of group I will exhibit enhanced durability compared to the SCC of group II.

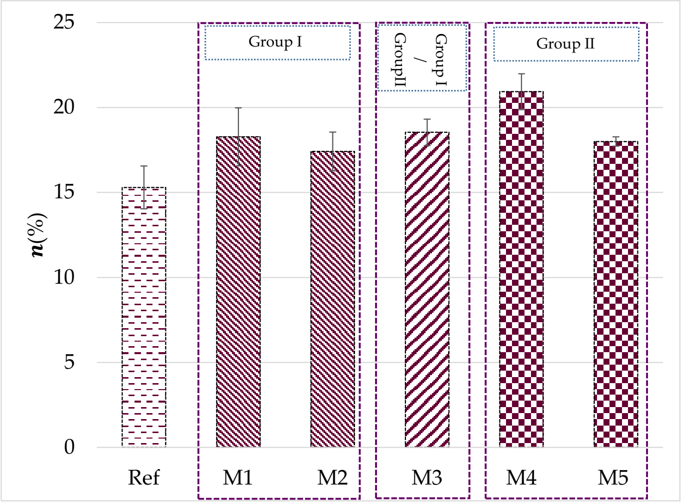

FIGURE 6. **Vacuum porosity of SCC at 28 days**

The results presented in Figure 7a demonstrate the evolution of the apparent density ($\boldsymbol{\rho_{app}}$). SCCs from Group II exhibit a lower density compared to those from Group I. This can be attributed to the more porous nature and lower density of the recycled gravels used in Group II. Additionally, Figure 7a describes that SCCs with a high content of ceramic brick (greater than 40%) can be classified as lightweight concrete. This suggests that the porous nature of brick significantly contributes to the reduction in SCC density.

Incorporating recycled gravel affects the properties of the concrete, making it more porous, which can influence its long-term durability and mechanical performance. The correlation between porosity "$\boldsymbol{n}$(%)" and apparent density($\boldsymbol{\rho_{app}}(\boldsymbol{kg/m^3})$)is illustrated in Figure 7b and expressed by Equation (2). This correlation is established based on the results of this study and supported by findings from the literature (Silva et al., 2016).

$$\boldsymbol{\rho_{app}}(\boldsymbol{kg/m^3}) = \boldsymbol{21324n}(\%)^{\boldsymbol{-0.805}} \qquad \text{With: } R^2 = 0.83 \qquad \textbf{(2)}$$

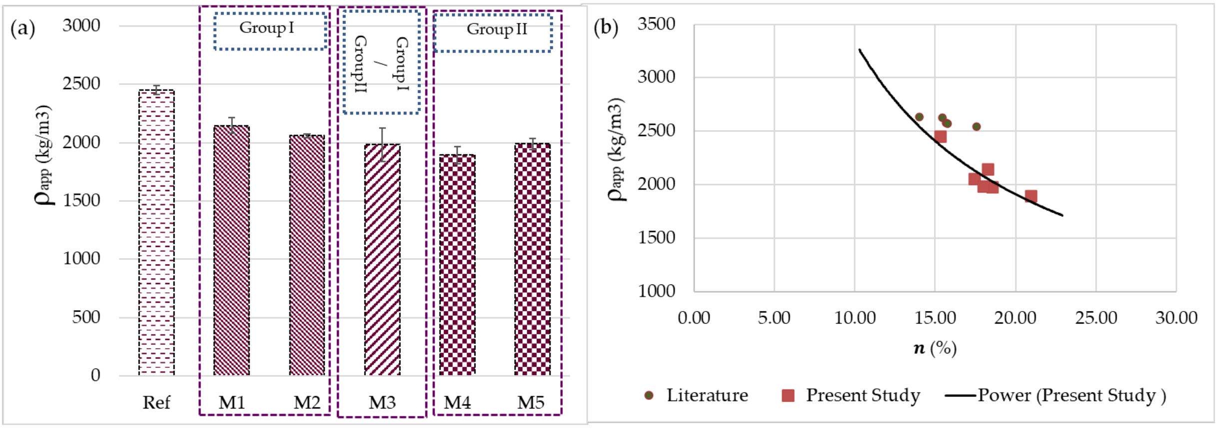

FIGURE 7. a) **Vacuum density of SCC at 28 days, b) correlation between porosity and density of SCC**

C. Mechanical properties of SCC

Figure 8 presents the mean compressive strength, f_{cm} , at 28 days. The results indicate that the compressive strength of SCCs in Group I (dominated by recycled concrete gravel, Rc) and Group II (dominated by recycled brick gravel, Rb) is reduced by 8.8% to 18.5% compared to the SCC mix with 100% natural gravel. The increase in the Rb ratio at the expense of Rc in the mixed recycled gravels results in the most significant decline in f_{cm} . The decrease of f_{cm} can be explained by the poor quality of the adhered old paste to natural gravel for Rc and the weakening of the interfacial transition zone (ITZ) between old and new paste (Safiullah Omary, 2016). For Rb, this is mainly attributed to the low resistance of the bricks.

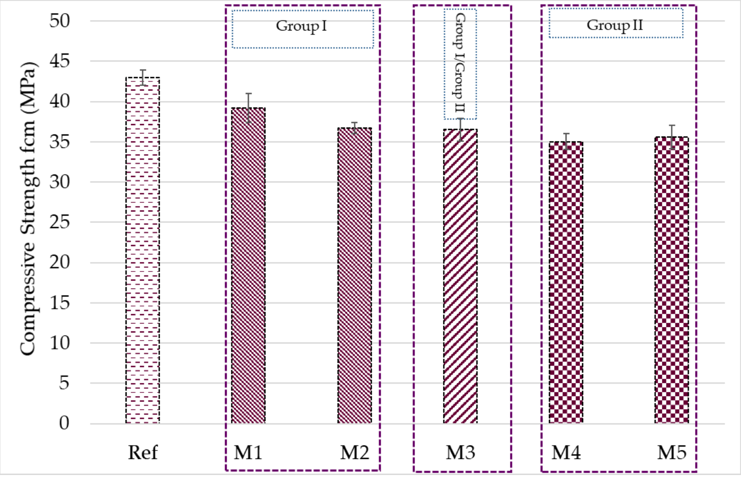

FIGURE 8. **Compressive Strength of SCC at 28 days**

The introduction of recycled gravels did not significantly reduce the tensile strength of the concrete mixes. Notably, the reference mix exhibits higher strengths compared to those containing recycled gravels sourced from various types of NHCDW. Mixes incorporating combinations of Rx, Rb2, Ra, and other recycled materials demonstrate slightly lower strengths. Figure 9a illustrates the splitting tensile strength of the six mixes. Upon closer examination of the failure surface following the splitting tensile strength test (Figure 9b), it is evident that the recycled brick gravels tended to fracture or "cut" under splitting tensile strength, whereas the natural gravel remained intact. This behavior can be attributed to the inherent material properties of recycled brick gravel compared to natural gravel. Recycled brick gravels typically possess lower mechanical strength and higher porosity due to their manufacturing process and prior use in construction. Additionally, the brittle nature of brick materials further contributes to their susceptibility to fracture during failure.

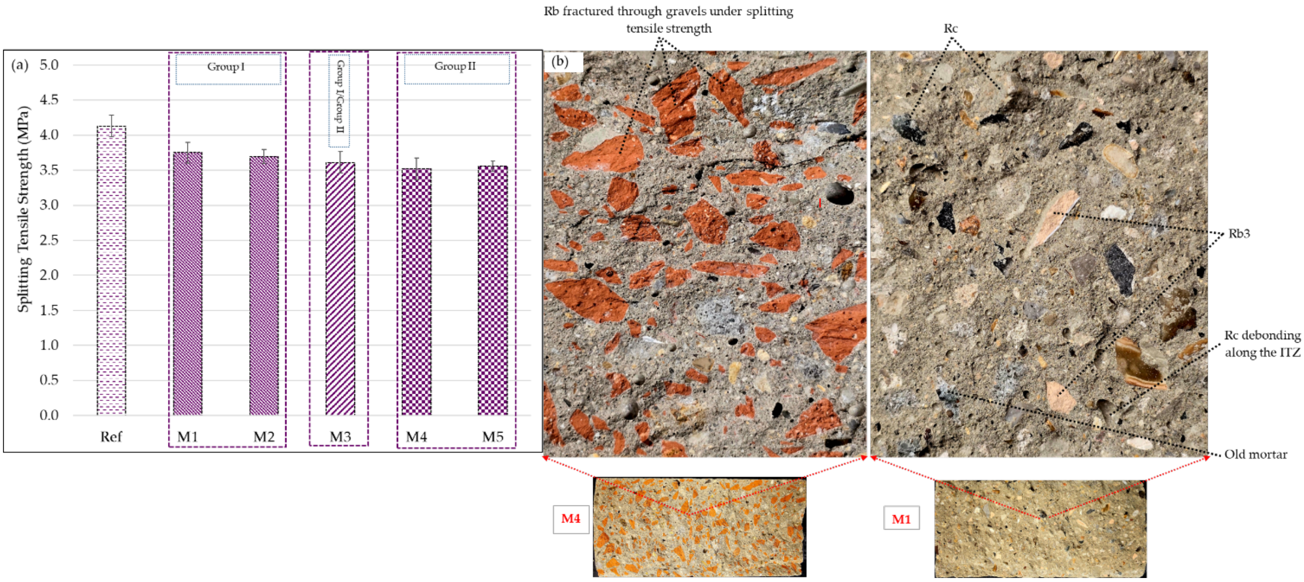

FIGURE 9. a) Splitting tensile Strength of SCC at 28 days, b) Failure Mode of SCC Under Splitting Tensile Strength

Figure 10 presents the relationship between splitting tensile strength (MPa) and compressive strength (MPa) for various formulations of SCC. The data presented include results from the current study as well as findings from various other research works (Islam et al., 2022),(Hilal et al., 2021),(Ahmed et al., 2023), (Mishra and Panda, 2020), (Duan et al., 2020), (Zrar et al., 2023), (Tang et al., 2023), (Rashwan et al., 2022),(Tang et al., 2016), (Silva et al., 2016), (Sun et al., 2020), (Revathi et al., 2013). Models such as EC2 (Eurocode2, 2004) and (Omary et al., 2018) have been employed to predict the splitting tensile strength (Equation 3). It appears that the EC2 model provides a more accurate estimation even if the difference between the models is not significant (Table 5). The model proposed by (Omary et al., 2018) tends to slightly underestimate the tensile strength, making it less precise for SCC.

$$f_{ctm,sp}=\eta_1(f_{cm})^{\eta_2} \tag{3}$$

where η_1 and η_2 are fitting parameters, which have been determined to be 0.364 and 0.608, respectively, irrespective of the type of aggregates. The new best-fit trend line, with η_1=0.389 and η_2= 0.608, closely aligns with experimental data, suggesting that modified models, particularly those accounting for recycled aggregates, offer more accurate predictions.

TABLE 5. Comparison of Model Parameters for Predicting $f_{ctm,sp}$

Proposed by	η_1	η_2	R^2
(Eurocode2, 2004)	0.3	$\frac{2}{3}$	0.61
(Omary et al., 2018)	0.364	0.608	0.58
Optimal Model (present Study)	0.389	0.608	0.60

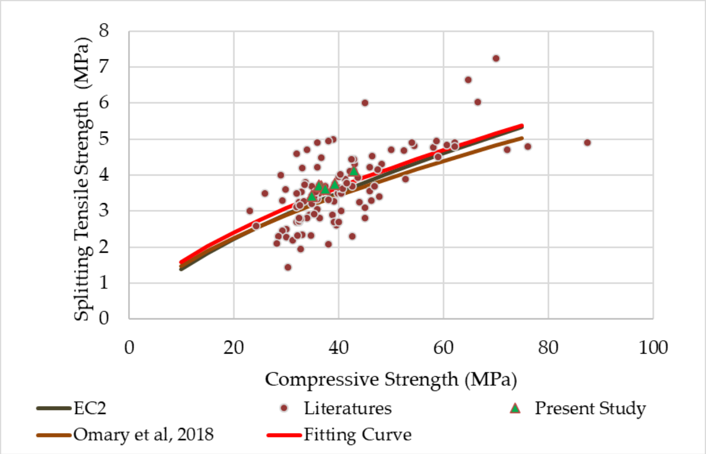

FIGURE 10. **Splitting tensile strength correlated with compressive strength**

IV. CONCLUSION

This study investigated the use of recycled coarse aggregates from NHCDW in self-compacting concrete to promote sustainability in the construction industry. The findings revealed that SCC with up to 85% Rc maintained satisfactory rheological and mechanical properties, demonstrating the feasibility of using Rc as a viable alternative to natural gravel. Replacing 85% of natural gravel with Rb resulted in an 18.5% reduction in compressive strength and a 14.8% reduction in splitting tensile strength. Furthermore, flexural strength decreased by 32% compared to the reference at 28 days. Consequently, this replacement ratio is not recommended for structural applications.

The study highlighted that the mechanical strengths, including compressive and tensile strength, decreased by 8.8% to 18.5% and 9.2% to 14.8%, respectively, compared to the reference. These findings provide valuable insights into the limitations and potential of using coarse aggregates from NHCDW materials for concrete applications. The research also emphasized the importance of pre-treatment methods, such as pre-moistening recycled gravels, to improve workability and reduce variations in mechanical performance, especially at higher substitution rates.

Based on the experimental results, several recommendations can be made for the further development and application of NHCDW gravels in concrete production. Firstly, the study confirms that coarse aggregates derived from NHCDW meet the necessary standards for concrete applications. Therefore, it is recommended that recycled gravels be further promoted in the construction industry, provided that proper pre-treatment methods are implemented to address issues related to water absorption and surface texture.

This research contributes to sustainable construction by providing guidelines for using recycled gravels in SCC, which lowers environmental impact and supports the circular economy. Future studies should focus on optimizing the use of other alkaline activators and exploring additional pre-treatment methods to enhance the performance of SCC incorporating recycled gravels.

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