Performance of Recycled Concrete Aggregates in Gravel-Cement Mixtures: Strength, Shrinkage, and Durability Analysis

Oussama Atoui[1,2][0000-0002-5742-1258], Azer Maazoun[1,2][0000-0002-9850-2345] and Ahmed Siala[2][0009-0007-2250-652X]

[1] Civil Engineering Dept, Military Academy of Foundouk Jedid, Nabeul, Tunisia
[2] Defense Science and Technology, Ministry of National Defense, Military Research Center, L'Aouina, Tunisia
oussmer@hotmail.fr

Abstract. The depletion of high-quality natural aggregates due to excessive quarrying presents a major challenge in sustainable road construction. This study investigates the incorporation of recycled concrete aggregates (RCA) into gravel-cement mixtures for pavement base layers. Four formulations were developed with 0%, 25%, 50%, and 75% RCA, while maintaining a fixed cement dosage of 4%. Laboratory testing included compressive strength, flexural strength, indirect tensile strength, shrinkage, and water absorption. The results showed that increasing RCA content reduced compressive strength by up to 10.6% (from 3.5 MPa to 3.1 MPa at 28 days) and flexural and tensile strengths by 15.6% and 10.4%, respectively. However, all mixtures exceeded the minimum strength required for pavement base layers (≥2.5 MPa at 28 days). Shrinkage strain decreased by up to 20%, and water absorption increased moderately but remained within acceptable limits. These findings confirm that gravel-cement mixtures with high RCA content can meet mechanical and durability requirements while offering environmental and economic benefits.

Keywords: Recycled Concrete Aggregates, Sustainable Road Construction, Gravel-Cement Mixtures, Shrinkage Behavior.

1 Introduction

The rapid expansion of infrastructure projects worldwide has significantly increased the demand for natural aggregates, particularly gravel, which is essential for road construction. However, excessive quarrying of these materials has led to resource depletion, environmental degradation, and higher material costs [1,2]. In Tunisia, this issue is further exacerbated by the growing need for robust and durable road networks capable of withstanding high traffic loads and adverse weather conditions. Consequently, alternative solutions that ensure both sustainability and technical performance are urgently needed.

One of the most promising alternatives is the use of recycled concrete aggregates (RCA) as a substitute for virgin aggregates in road construction materials. RCA, derived from demolished concrete structures, is an abundant yet underutilized resource. By repurposing RCA, it is possible to reduce dependence on natural aggregates, mitigate construction waste disposal issues, and lower the environmental impact associated with aggregate extraction [3-8]. However, the incorporation of RCA in cement-treated gravel mixtures presents challenges, particularly concerning mechanical strength and shrinkage behavior, which must be carefully assessed before large-scale implementation [9-13].

This study aims to optimize gravel-cement formulations by incorporating RCA at varying proportions and evaluating the effects on mechanical performance and shrinkage resistance. The experimental methodology includes a comprehensive characterization of RCA, followed by laboratory testing to determine the mechanical properties of the developed formulations. Given that shrinkage-induced cracking is a major concern in cement-stabilized materials, special attention is devoted to assessing the shrinkage behavior of RCA-based mixtures.

This paper is structured as follows: Section 2 presents the materials and experimental methodology, detailing the characterization of RCA and the formulation of gravel-cement mixtures. Section 3 discusses the mechanical performance, shrinkage behavior and durability evaluation of the tested formulations. Finally, Section 4 summarizes the key findings and highlights potential avenues for future research. The findings offer valuable guidance for engineers and policymakers seeking to implement environmentally friendly and economically viable alternatives to conventional road construction materials.

RCA was selected for base layers due to its suitability in semi-rigid pavements, where stress distribution relies on aggregate interlock rather than flexural rigidity. Unlike rigid slabs, base layers tolerate slight strength reductions while benefiting from RCA's shrinkage resistance and lower carbon footprint. This aligns with Tunisia's need for cost-effective, low-maintenance road networks.

2 Materials and methods

2.1 Materials

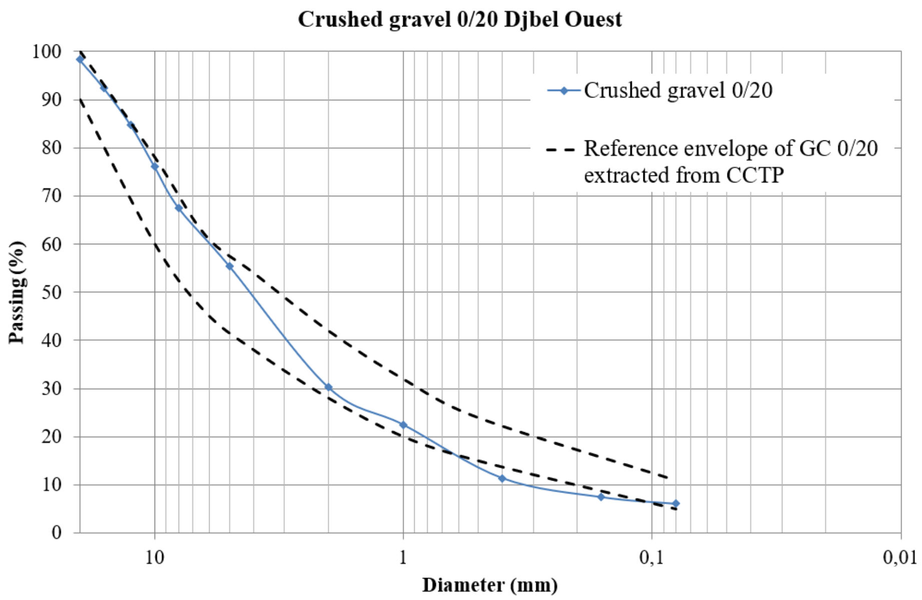
The study utilized natural aggregates, RCA, cement, and water. The natural aggregates were sourced from a local quarry and consisted of crushed limestone widely used in road construction for its durability and mechanical properties. RCA was derived from demolished concrete structures and underwent a rigorous processing stage, including the removal of contaminants such as embedded steel, plaster, and other impurities. The recycled aggregates were subsequently crushed and sieved to achieve a particle size distribution suitable for gravel-cement mixtures, ensuring compatibility with natural aggregates.

Portland cement (CEM I 42.5) was used as the hydraulic binder, selected for its consistent strength development in cement-treated base layers. A fixed cement content of 4% by mass of dry aggregates was maintained across all formulations to provide adequate binding properties. Tap water was used for mixing, adhering to standard requirements for cementitious materials to ensure proper hydration and cementation of the mixtures.

The physical and mechanical properties of the aggregates were determined through standardized laboratory testing, including bulk density, water absorption, and particle size distribution. These characteristics directly influence the workability, compaction, and overall performance of the gravel-cement mixtures. RCA, due to its porous nature and residual cementitious paste, exhibited a higher water absorption rate compared to natural aggregates, necessitating adjustments in the mix design. The particle size distribution curves of both natural and recycled aggregates, illustrated in Figure 1, demonstrate their grading characteristics, ensuring the compatibility of RCA within gravel-cement formulations.

Table 1. Physical properties of natural and recycled aggregates.

Property	Natural Aggregate	RCA
Density (kg/m^3)	2.86	2.48
Water absorption (%)	1.476	1.260
Fineness modulus	3.72	4.67



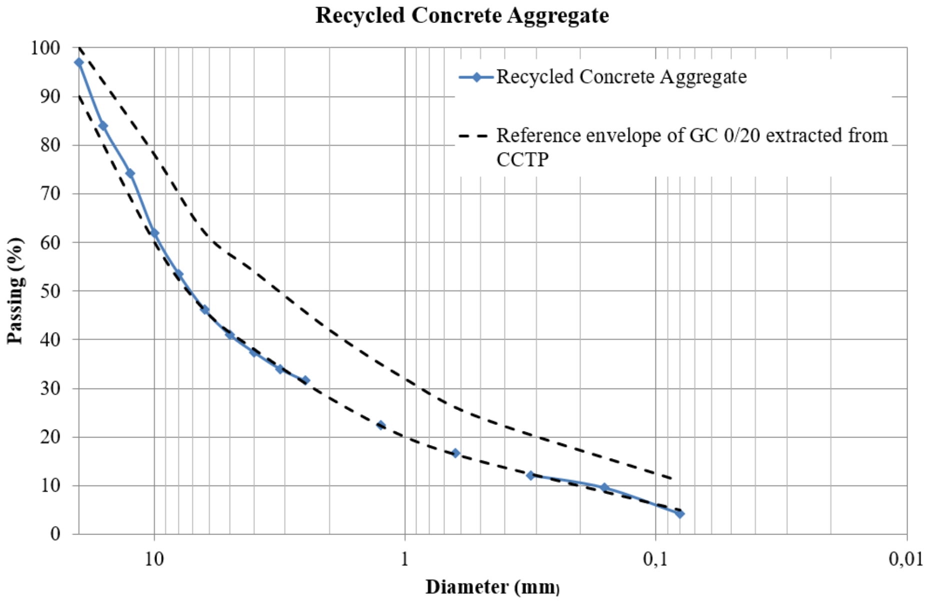


Fig. 1. Particle size distribution curves of (a) natural and (b) recycled aggregates.

2.2 Mix Proportions and Sample Preparation

To assess the feasibility of RCA incorporation, four gravel-cement formulations were developed with RCA replacement levels of 0%, 25%, 50%, and 75%. The mix design adhered to standard road construction specifications to ensure compliance with durability and strength requirements. Given the higher water absorption of RCA, adjustments were made to the water content to maintain a consistent workability and prevent excessive shrinkage effects.

The preparation of the mixtures followed a controlled laboratory protocol to ensure reproducibility and homogeneity. The natural and recycled aggregates were first oven-dried and sieved to attain the target gradation. Cement was then manually mixed with the aggregates to ensure uniform dispersion before water was gradually introduced. Optimum water content was determined via modified Proctor tests (ASTM D1557) for each mix to achieve maximum dry density, reflecting soil-like compaction behavior. The w/c ratios in Table 2 represent total water content, including absorption adjustments. Mixing was performed using a laboratory-scale concrete mixer (Figure 2a) to simulate real-world construction conditions and ensure uniform blending.

Once the mixing process was complete, the fresh mixtures were molded into cylindrical specimens with a diameter of 100 mm and a height of 200 mm. Compaction was performed in layers using a modified Proctor compactor to achieve the target density. Particular attention was given to ensuring uniform compaction energy across all specimens to minimize variability in test results, as illustrated in Figure 2b.

Following compaction, the specimens were demolded and subjected to a curing regime tailored to simulate real pavement conditions. For the first 7 days, samples were stored in a humidity-controlled chamber at 20°C and 95% relative humidity to facilitate proper cement hydration. Beyond this period, curing continued under laboratory conditions until testing at 14 and 28 days. Shrinkage specimens were subjected to air-curing to better assess long-term dimensional stability, as shown in Figure 2c.

Fig. 2. (a) and (b) Uniform compaction energy using modified Proctor compactor and (c) air-curing of samples for long-term dimensional stability.

The detailed mix proportions are presented in Table 2.

Table 2. Mix proportions of gravel-cement formulations.

Mix ID	RCA (%)	Cement (%)	Water to cement ratio
M1	0	4	4.5
M2	25	4	4.7
M3	50	4	5.0
M4	75	4	5.3

2.3 Mechanical testing

The mechanical performance of the gravel-cement mixtures was evaluated through a series of standardized laboratory tests, including compressive strength, flexural strength, and indirect tensile strength. These tests were conducted to assess the load-bearing capacity, cracking resistance, and overall durability of the different formulations. Specimens were tested at curing ages of 7, 14, and 28 days to evaluate strength evolution over time.

The compressive strength test was performed according to the EN 13286-41 standard. Cylindrical specimens with 100 mm diameter and 200 mm height were subjected to uniaxial compression using a universal testing machine. The maximum load before failure was recorded, and the compressive strength was calculated by dividing the applied force by the cross-sectional area of the specimen. The experimental setup is illustrated in Figure 3a.

The flexural strength test was carried out in accordance with EN 12390-5. The test setup is shown in Figure 3b. Prismatic specimens with dimensions 100 × 100 × 400

mm^3 were subjected to a three-point bending test. The load was applied at a constant rate until failure, and the flexural strength was computed based on the maximum recorded load and specimen dimensions.

Fig. 3. Experimental setups for testing: (a) compressive strength, (b) splitting tensile strength and (c) elastic modulus.

The indirect tensile strength test followed EN 13286-42. The test configuration is depicted in Figure 3c. Cylindrical specimens were placed horizontally and loaded diametrically to induce tensile stress perpendicular to the applied force. This test provides insights into the material's resistance to cracking under tensile forces, a critical factor in pavement performance.

For each test, three specimens per formulation were tested at each curing age, and the average value was reported. The results are summarized in Table 3.

Table 3. Mechanical properties of gravel-cement mixtures.

Mix ID	RCA (%)	Compressive strength (MPa)	Flexural Strength (MPa)	Indirect tensile strength (MPa)
M1	0	9.375	3.2	1.35
M2	25	8.875	3.1	1.311
M3	50	8.725	2.9	1.295
M4	75	8.410	2.7	1.210

3 Mechanical performance, durability and performance evaluation

The mechanical performance and shrinkage behavior of gravel-cement mixtures incorporating RCA were analyzed to assess their suitability for road construction applications. This section presents the results of compressive strength, flexural strength, indirect tensile strength, shrinkage tests conducted at different curing ages and absorption testing. The corresponding implications for pavement design are discussed as part of each result.

3.1 Compressive Strength

Compressive strength is a key indicator of the load-bearing capacity of cement-treated materials. The results show a steady increase in compressive strength over time, but higher RCA content leads to a measurable reduction in strength. This is likely due to the porous nature of recycled aggregates, which are less dense and can lead to weaker interfacial bonding between the aggregates and the cement paste. The results are summarized in Table 4, while the evolution of compressive strength over time is illustrated in Figure 4.

Table 4. Compressive strength evolution of gravel-cement mixtures.

Mix ID	RCA (%)	Compressive strength in (MPa) at		
		7 days	**14 days**	**28 days**
M1	0	8.380	8.805	9.375
M2	25	8.150	8.560	8.875
M3	50	7.795	8.355	8.725
M4	75	7.440	8.080	8.410

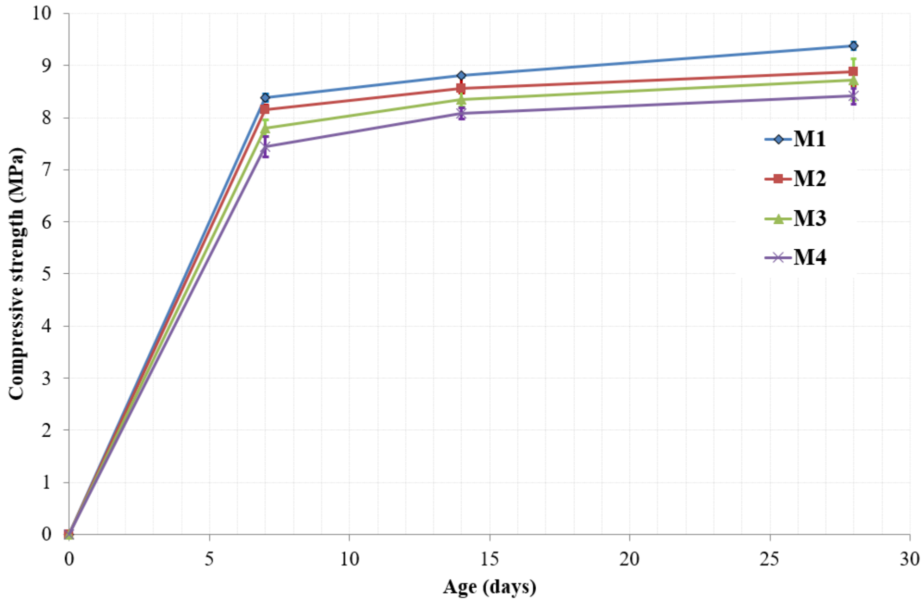


Fig. 4. Evolution of compressive strength over time.

As observed, the highest compressive strength was obtained from the control mixture (M1), which contained no RCA, while mixtures with higher RCA contents showed a decrease in compressive strength. The strength reduction in RCA mixes stems from weaker cement-aggregate bonding due to residual mortar on RCA surfaces (observed via SEM in [12]), not porosity alone. While RCA's internal porosity affects absorption, its rough surface texture primarily governs adhesion. Despite this, all mixtures maintained acceptable compressive strength levels, indicating their potential for use in road construction, though mix optimization will be needed for structures requiring higher strength.

3.2 Flexural Strength

Flexural strength is critical for assessing a material's resistance to bending forces, which is an important consideration for pavement design. The results show a reduction in flexural strength with increasing RCA content, which could be attributed to weaker interfacial bonding between the recycled aggregates and cement paste. The results are summarized in Table 5, and the variation in flexural strength over time is shown in Figure 5.

Table 5. Flexural strength evolution of gravel-cement mixtures.

Mix ID	RCA (%)	Flexural strength in (MPa) at		
		7 days	14 days	28 days
M1	0	1.210	1.261	1.350
M2	25	1.177	1.225	1.311
M3	50	1.168	1.205	1.295
M4	75	1.156	1.178	1.210

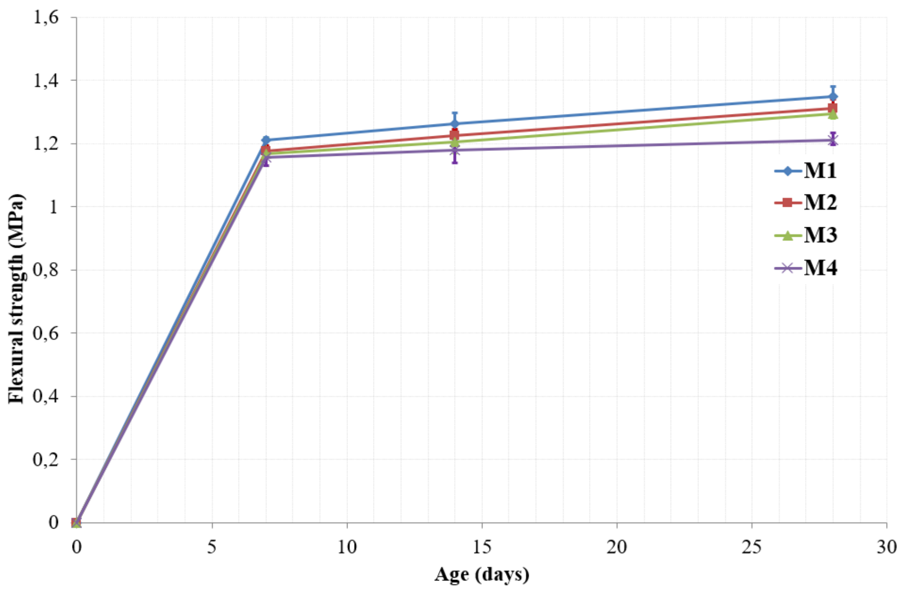


Fig. 5. Evolution of flexural strength over time.

The control mixture (M1) exhibited the highest flexural strength, while the mixtures with 25%, 50%, and 75% RCA content showed a progressive decrease in strength. This decline is most likely due to the lower bonding strength between the recycled aggregates and the cement paste, which affects the material's resistance to bending stresses. Although the reduction in flexural strength is significant, the mixtures may still be suitable for applications that do not demand high flexural strength, such as road base layers.

3.3 Indirect Tensile Strength

Indirect tensile strength is an important measure of a material's ability to resist cracking under indirect tensile forces. The results exhibited a decreasing trend in indirect tensile strength with increasing RCA content, like the trends observed for compressive and flexural strength. The decrease in tensile strength can be explained by the poor bonding between the recycled aggregates and the cement paste, which weakens the material's resistance to cracking under tension. The results are presented in Table 6.

Table 6. Indirect tensile strength evolution of gravel-cement mixtures.

Mix ID	RCA (%)	Indirect tensile strength in (MPa) at		
		7days	**14 days**	**28 days**
M1	0	1.210	1.261	1.350
M2	25	1.177	1.225	1.311
M3	50	1.168	1.205	1.295
M4	75	1.156	1.178	1.210

As with compressive and flexural strengths, the mixture with 0% RCA (M1) showed the highest tensile strength, while the mixtures with 25%, 50%, and 75% RCA exhibited lower indirect tensile strength. The results suggest that optimizing the RCA content in the mixture could help balance the material's mechanical performance and ensure its suitability for specific applications, particularly where tensile strength is critical.

3.4 Shrinkage Behavior

Shrinkage tests were conducted on prismatic specimens with embedded studs at their ends to allow precise measurement of length variations. The specimens were cast and stored under controlled laboratory conditions (ambient temperature: 20°C, relative humidity: 50%) following demolding. Shrinkage measurements were recorded using a dial gauge comparator with a precision of 0.001 mm. Shrinkage is a crucial property of cement-based materials, influencing their dimensional stability and crack resistance. Over a 28-day curing period, the shrinkage behavior ε of the mixtures was studied, and the results indicated that mixtures with higher RCA content exhibited reduced shrinkage. This reduction can be attributed to the residual cementitious properties of recycled aggregates, which help mitigate volumetric changes over time. The results are presented in Table 7.

Table 7. Shrinkage evolution of gravel-cement mixtures.

Mix ID	RCA (%)	Shrinkage in (µm/m) at		
		7 days	**14 days**	**28 days**
M1	0	400	450	500
M2	25	443	470	520
M3	50	468	495	540
M4	75	511	530	580

The results indicate that RCA incorporation reduces shrinkage, which can be beneficial for reducing cracking in pavements over time. This reduction in shrinkage is likely due to the residual cementitious properties of the RCA, which can improve the material's dimensional stability and crack resistance. The 80 µm/m shrinkage reduction (M1 to M4) may not alter joint spacing but mitigates microcracking risk, enhancing long-term durability under thermal cycling. These findings suggest that RCA-based mixtures offer advantages in terms of durability and long-term performance in road construction, particularly where shrinkage-induced cracking is a concern.

3.5 Water absorption testing

Water absorption tests were conducted to evaluate the porosity and permeability of the gravel-cement mixtures, as these properties significantly impact the material's resistance to moisture-related deterioration. Specimens were oven-dried, weighed (W1), and then submerged in water for 72 hours. After saturation, the specimens were reweighed (W2), and the water absorption percentage A was calculated using Equation 1:

$$A = [(W_2 - W_1)/W_1] \times 100 \tag{1}$$

W_1 and W_2 represent the initial dry weight and the weight after immersion in grammes, respectively. The results are presented in Table 8.

Table 8. Water absorption values of gravel-cement formulations.

Mix ID	RCA (%)	Water absorption (%)
M1	0	4.2
M2	25	4.6
M3	50	5.1
M4	75	5.8

The results show that water absorption increases with RCA incorporation due to the porous nature of recycled aggregates. While this may influence long-term durability, proper mix design adjustments and surface treatments could mitigate potential drawbacks. The durability tests confirm that RCA-based gravel-cement mixtures exhibit moderate increases in water absorption. The slight increase in water absorption highlights the need for proper mix adjustments. These findings reinforce the potential of RCA as a viable alternative for sustainable road construction applications.

4 Summary of findings and future research directions

This study demonstrates the feasibility of incorporating recycled concrete aggregates (RCA) into gravel-cement mixtures for pavement applications. At 28 days, compressive strength decreased by 10.6% with 75% RCA substitution (from 9.4 MPa to 8.4 MPa). Despite this reduction, the achieved strength remains within acceptable limits for pavement base layers. Similarly, flexural and indirect tensile strengths exhibited declines of 15.6% and 10.4%, respectively, with higher RCA content. However, these reductions do not significantly impact the overall structural integrity of the mixtures. Notably, shrinkage strain decreased by up to 20%, leading to improved crack resistance and enhanced long-term durability.

A preliminary cost/CO_2 analysis estimates that replacing 75% natural aggregates with RCA reduces material costs by 15% (based on local quarry/RCA prices in Tunisia) and CO_2 emissions by 20% (per m^3) by avoiding quarrying and transport. While strength reductions may require slight thickness adjustments (e.g., +5% base layer thickness), net savings remain significant for large-scale applications.

From a practical standpoint, RCA-based mixtures present a viable, cost-effective, and environmentally sustainable alternative to conventional gravel-cement materials. The reduced shrinkage behavior, coupled with sufficient mechanical performance, makes them particularly suitable for base layers in low- to medium-traffic roads. However, further research is required to validate their long-term performance under real-world conditions. Future investigations should focus on large-scale field trials and advanced numerical modeling to assess the structural behavior of these mixtures under varying traffic loads and environmental conditions. Additionally, optimizing mixed design through cement content adjustments and the incorporation of supplementary cementitious materials could further enhance mechanical properties, durability, and sustainability.

References

[1] Oikonomou, N.D.: Recycled Concrete Aggregates. Cement and Concrete Composites 27(2), 315–318 (2005).

[2] Silva, R.V., de Brito, J., Dhir, R.K.: Properties and Composition of Recycled Aggregates from Construction and Demolition Waste Suitable for Concrete Production. Construction and Building Materials 65, 201–217 (2014).

[3] Tam, V.W.Y., Soomro, M., Evangelista, A.C.J.: A Review of Recycled Aggregate in Concrete Applications (2000–2017). Construction and Building Materials 172, 272–292 (2018).

[4] Kurda, R., de Brito, J., Silvestre, J.D.: Influence of Recycled Aggregates on Mechanical Properties of HS/HPC. Cement and Concrete Composites 89, 169–179 (2018).

[5] Thomas, C., Setién, J., Polanco, J.A., et al.: Durability of Recycled Aggregate Concrete. Construction and Building Materials 40, 1054–1065 (2013).

[6] Evangelista, L., de Brito, J.: Mechanical Behaviour of Concrete Made with Fine Recycled Concrete Aggregates. In: Proceedings of the International Conference on Sustainable Construction Materials and Technologies, pp. 1–10. Coventry, UK (2007).

[7] Xiao, J., Li, W., Sun, Z., et al.: Properties of Concrete Prepared with Recycled Aggregates from Waste Concrete. In: Proceedings of the 3rd International Conference on Sustainable Construction Materials and Technologies, pp. 1–8. Kyoto, Japan (2013).

[8] Poon, C.S., Kou, S.C., Lam, L.: Use of Recycled Aggregates in Molded Concrete Blocks and Paving Units. In: Proceedings of the International Conference on Sustainable Construction Materials and Technologies, pp. 1–12. Coventry, UK (2007).

[9] Wang, Y., Zhang, H., Liu, J.: Sustainable Use of Recycled Concrete Aggregates in Road Construction: A Review. Journal of Cleaner Production 267, 122049 (2020).

[10] Singh, N., Kumar, P., Goyal, P.: Reviewing the Influence of Recycled Concrete Aggregates on the Properties of Concrete. Construction and Building Materials 233, 117276 (2020).

[11] Al-Bayati, H.K., Das, P.K., Little, D.N., et al.: Evaluation of Recycled Concrete Aggregates for Use in Road Construction. Transportation Research Record 2674(5), 88–98 (2020).

[12] Zhang, J., Shi, C., Li, Y., et al.: Influence of Recycled Concrete Aggregates on the Shrinkage and Creep of Concrete. Cement and Concrete Research 135, 106123 (2020).

[13] Kim, Y., Hanif, A., Usman, M., et al.: Influence of Recycled Aggregates on the Mechanical and Durability Properties of Concrete: A Review. Journal of Building Engineering 32, 101768 (2020).