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Valorization potential of post-earthquake controlled demolition waste for circular construction materials: Field-laboratory assessment of recycled aggregates in Türkiye

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ABSTRACT

This study evaluates the valorization potential of recycled concrete aggregates (RCAs) and recycled mixed aggregates (RMAs) obtained from post-earthquake controlled demolition waste (DW) in Türkiye for use in road construction, concrete production, and cement manufacturing. The samples were collected from controlled demolition of buildings constructed in different periods, reflecting revisions of the Turkish Seismic Codes, as well as from a Temporary Storage Site (TSS) representing mixed debris. A comprehensive experimental program was conducted to assess the physical, mechanical, durability-related, and chemical properties of the recycled aggregates (RA). The findings reveal relationship between building construction age and RA quality. RCAs derived from buildings showed better performance; higher density, lower water absorption, improved abrasion, freeze–thaw resistance, and lower chemical reactivity, making it more suitable for road base and subbase layers as well as for concrete and cement production than RMA. In contrast, RMA showed limited applicability due to its heterogeneous composition. The variability of DW samples obtained from a TSS underscores the importance of source-based separation to maintain RA quality. Overall, the study establishes a scientific framework by demonstrating how seismic-code-oriented building classifications serve as a primary indicator for the valorization potential of DW. This approach moves beyond generic building age, providing a predictive methodology for identifying high-quality secondary resources in disaster-prone regions, thereby supporting targeted circularity in structural materials.

1. Introduction

The transition from linear "take-make-dispose" construction models to circular economy approaches is critical for sustainable urban development. Circular economy principles prioritize waste valorization viewing demolition materials as secondary resources rather than disposal liabilities. The amount of construction and demolition waste (CDW) increases with urbanization, and these wastes can constitute up to 35% of total waste in developed countries and 50% in developing countries [1,2] In the United States, approximately 600 million tons of CDW are generated annually [3]. In the European Union (EU), the amount of CDW in 2022 is 860 million tons, accounting for 38.4% of total waste [4].

Beyond routine urban development, natural hazards most notably earthquakes may trigger abrupt and massive surges in CDW volumes, often overwhelming existing management infrastructures. Historical events underscore this volatility: the 1995 Kobe earthquake (Japan) generated approximately 15 million tons of debris [5], while the 1999 Marmara earthquake (Türkiye) produced an estimated 13 million tons [6]. Such extraordinary volumes typically exceed the operational capacity of regional solid waste facilities and requiring specialized valorization strategies for post-disaster recovery [7].

The February 6, 2023 (Kahramanmaraş) earthquake sequence hit southeastern of Türkiye and caused widespread damage across 11 cities. According to the Presidency of the Republic of Türkiye Strategy and Budget Office (SBO), the earthquakes affected 14 million people in the

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region, representing 16.4% of Türkiye's total population of 85.7 million [8]. After an earthquake, the waste generated is largely DW due to the removal of collapsed, to be urgently demolished and heavily damaged structures [9]. Aftermath of the 2023 Kahramanmaraş earthquakes (Türkiye), SBO reported the distribution of buildings in the earthquakes-affected region as follows; 43.5% of the buildings were constructed before 2000, 47.4% of the buildings constructed after 2000 and 9.1% of the construction year of buildings were unknown [8]. In addition, in terms of load-bearing systems at the earthquake affected region, 86.7% of buildings were reinforced concrete (RC) while the remaining buildings are as follows: 2.4% steel; 3.5% masonry; and 3.6% prefabricated and other category (3.9%) [8].

While concrete is the most used construction material, concrete production causes a wide sustainability concern due to the consumption of natural resources. Concrete itself accounts for 50–70% of CDW worldwide [10] with 20 billion tons usage per year [11]. This trend aligns with the global surge in aggregate demand; worldwide production of virgin aggregates rose from 21 billion tons in 2007–50 billion tons in 2017, with projections reaching 60 billion tons by 2030. Within this global landscape, Türkiye accounts for approximately 0.96% of the total aggregate consumption [12]. In the United States, about 2.7 billion tons of aggregates are produced while 10–15% of it used for paving, 20–30% for road construction and 60–70% for structural concrete in buildings [13]. Recovery and recycling of debris provides significant opportunities in terms of conservation of natural resources, reduction of carbon emissions and economic savings [14]. Life cycle assessment (LCA) analyses reveal that incorporating recycled aggregates (RA) can reduce CO_2 emissions by 30–40%. Furthermore, innovative sequestration methods like accelerated carbonation can capture up to 50 kg of CO_2 per ton of RCAs, effectively storing carbon within the concrete matrix and enhancing material sustainability [12].

Concrete waste is extensively utilized as aggregate in various construction materials: 20–45% in concrete products, up to 50% as road materials, 100% in road fill layers and 3.9% raw material in clinker production [15].

The utilization of recycled concrete aggregates (RCA) provides multiple environmental and economic advantages, conservation of natural resources, lower total energy consumption, and the minimization of disposal needs through the use of CDW as a collective secondary resource [16,17]. Valorization of demolition waste (DW) can be achieved by using it as a substitute for natural aggregates (NAs) for different purposes. Findings revealed that post-earthquake controlled-demolition debris can be valorized in various applications, including concrete production, clinker production in the cement industry, asphalt material, and brick and tile manufacturing [15,18].

In road construction and geotechnical applications, RCAs have been identified as a high-quality alternative to NAs, particularly, when properly graded and compacted. Studies demonstrated that RCA can meet or exceed the requirements for base and subbase layers [19,20]. Sas [19] stated that RCA is a high-quality alternative to NAs as the road foundation or sub-base material. Studies have shown that the integration of supplementary recycled materials has led to improvements in strength, stiffness, and load-bearing capacity for roadway applications [21–23]. In addition, Akbas et al. [24] investigated the potential for utilizing RCA derived from DW, which met specifications for base and subbase materials.

Furthermore, RCA typically exhibits higher mechanical properties compared to recycled masonry or brick aggregates, particularly within higher-strength concrete classifications. Studies were carried out regarding the mechanical properties of concrete with RCA, and the behavior of structural elements constructed using RCAs were also evaluated [25,26]. Most studies concluded that, with proper mix proportioning and adequate quality control, concrete incorporating RCA can achieve mechanical and durability performance comparable to that of concrete made with NA. However, technical challenges remain as the presence of adhered mortar and higher porosity in RCAs generally lead to reduced mechanical performance and durability. These factors result in weaker interfacial transition zones (ITZs), which compromise the overall integrity of the concrete matrix. Statistical trends suggest that a 100% replacement of NAs with RCAs may reduce compressive strength to approximately 79% of conventional levels. To mitigate these effects, the use of supplementary cementitious materials (SCMs) like fly ash or silica fume (SF) is essential to refine the ITZ and enhance the bond between the RCAs and the cement paste [12].

On the other hand, several studies have employed RCA as a substitute (recycled concrete fines (RCF)) for clinker in cement production or as a SCM [27]. Ilcan [18] showed that the recycling and valorization of concrete waste from the 2023 Kahramanmaraş earthquakes were suitable for applications when high strength was not required. Different valorization studies were conducted for the utilization of RCA from DW. However, in most of these studies, it is observed that the RCA was selectively recycled. In this case, it is seen that only the concrete material was used for the recycle purposes. However, the DW consists not only concrete, but also a wide variety of different materials [28]. In the literature on RCAs, most studies focus on controlled material streams. Limited attention has been given to highly heterogeneous recycled materials derived from post-earthquake-controlled demolition activities, where RCAs coexist with recycled mixed aggregates (RMAs). The performance of these recycled materials is further influenced by regional disparities and the age of the demolished structures. RCAs sourced from older buildings often contain higher proportions of masonry or plaster, which negatively affect strength and durability compared to those derived from newer, concrete-rich demolitions [12]. While recent literature acknowledges that the age of demolished structures influences the physical properties of RCAs, there is a lack of research linking aggregate performance directly to the evolution of structural design codes. The scientific contribution of this study lies in its integrated methodology that classifies DW according to three distinct Turkish Seismic Code eras. This regulatory-based assessment provides a more precise and standardized categorization for waste streams than chronological age alone, offering a scalable framework for disaster waste management and high-value circularity pathways in earthquake-prone countries.

This gap requires an integrated field and laboratory-based assessments to evaluate application-specific suitability and to define realistic valorization pathways. To address this gap, this study employs a comprehensive, field and laboratory-based methodology designed to obtain mixed aggregates, and concrete samples reflecting actual conditions in demolition site. The approach integrates primary samples from field with supported by laboratory experiments. The study aimed at two objectives: (i) assessment of valorization potential of RMAs and RCAs obtained from post-earthquake controlled-demolition activities in Türkiye by evaluating their properties for road construction, concrete and cement production within the scope of the circular economy by demonstrating closed-loop material flows from post-disaster waste streams to infrastructure applications, (ii) to assess the impact of the building's age on RMA and RCA quality in accordance with the Turkish Seismic Code implemented in Türkiye. Addressing this knowledge gap is critical for both developing and developed countries. The study contributes not only to post-earthquake recovery efforts but also to ongoing CDW management practices.

2. Material and methods

This section comprises two components: (i) the field study, and (ii) laboratory analysis. The procedures for each component are detailed in the following subsections.

2.1. Field study

2.1.1. Study area

A multi-staged field study was conducted in Malatya Province which

is one of the cities most severely affected by 2023 Kahramanmaraş Earthquake sequence. The city was selected for two reasons: (i) its proximity to the epicentral region of the second mainshock, and (ii) the comparatively systematic implementation of controlled demolition and debris-management practices during the post-disaster response. Schematic illustration of the methodology of the study and the steps followed during the fieldwork and laboratory analysis in a systematic flow are given in Fig. 1.

First, building-level information (type and year of construction, and location) was collected from district municipalities, and a set of structures from different construction periods was selected for sampling. Selected buildings were then demolished in controlled conditions, and the resulting DW was transported to a Temporary Storage Site (TSS). Subsequently, DW samples were taken from randomly selected truckloads. Samples obtained from buildings and TSS were classified into two fractions as mixed debris and concrete-dominant material. These fractions were crushed and sieved separately to produce RCAs and RMAs of various sizes. A comprehensive laboratory program including physical, chemical, durability, and geotechnical tests was then performed to characterize their suitability as road materials, concrete aggregates, and additives for cement. Based on the test results, the feasible end-use pathways of the produced RAs for road construction, concrete, and cement production were assessed, and their value-added potential within the context of a circular economy was analyzed.

2.1.2. Data collection and selection of buildings

In this phase of the study, building data were obtained from the Yeşilyurt and Battalgazi District Municipalities, which maintain demolition plans for buildings requiring urgent demolition. Heavily damaged RC buildings were selected based primarily on construction year in order to investigate how changes in seismic design regulations (as reflected in the Turkish Seismic Code [29]) influence DW characteristics. The building stock was grouped into three construction periods: pre-2000, 2000–2011, and 2011–2018. This classification is based on the major

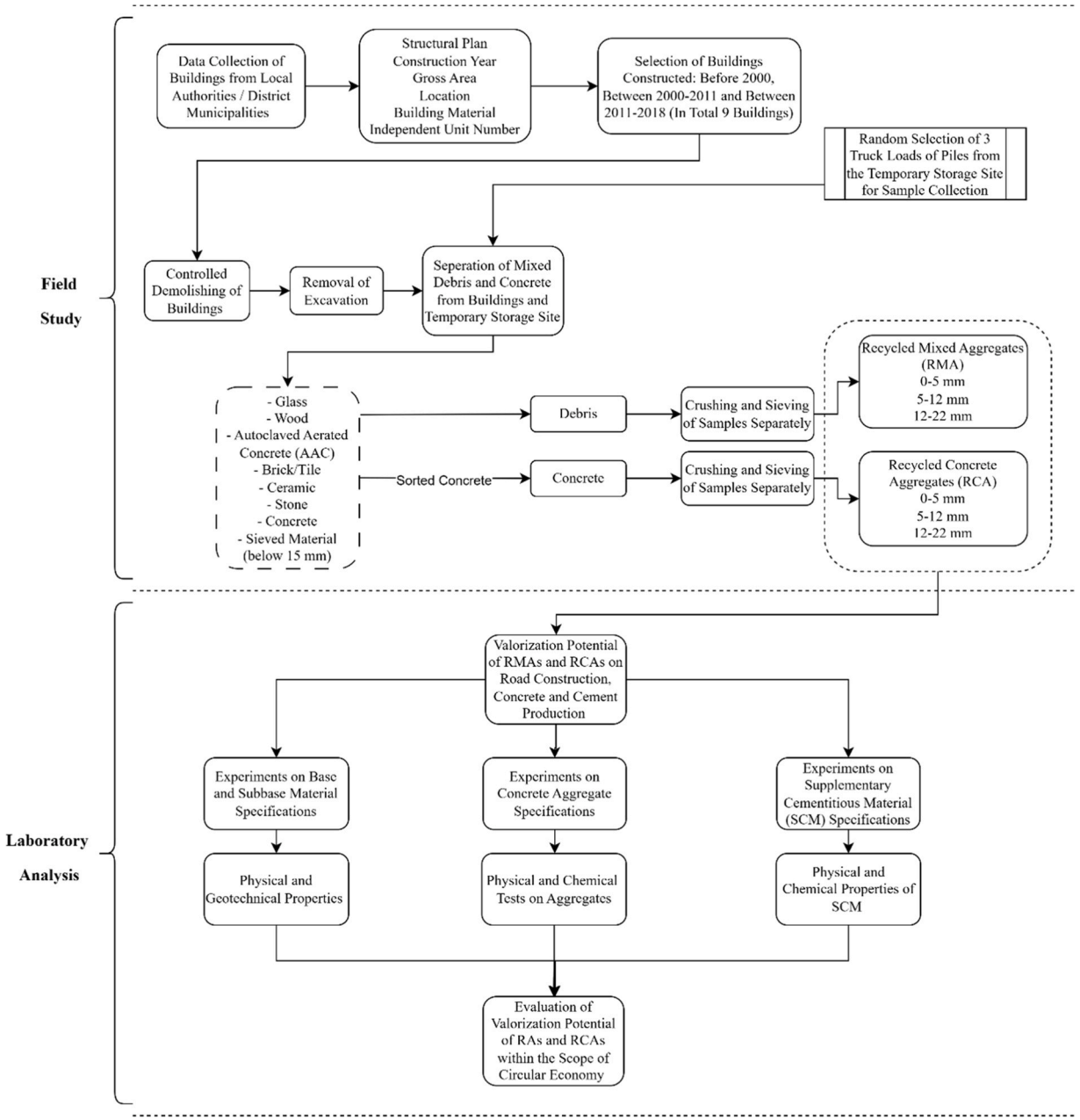


Fig. 1. Schematic illustration of the methodology.

milestones in Türkiye's seismic design and construction practice. The year 2000 is treated as a critical breakpoint, shaped by the enforcement of the updated 1998 Seismic Code [30], the lessons learned from the 1999 Kocaeli and Düzce earthquakes, the 2000 revision of TS500 [31] for RC design, and the increasing adoption of ready-mix concrete and deformed reinforcement. In parallel, the Building Inspection Law-2001 [32], initially implemented in 19 pilot provinces, including Gaziantep and Hatay, was expanded nationwide in 2011, marking the systematic enforcement of building inspection requirements. The 2011–2018 period therefore represents buildings constructed under countrywide inspection implementation and the prevailing seismic code framework prior to the subsequent regulatory update [33,34]. A total of nine buildings were selected, with three buildings representing each construction period (Figure S1). To improve representativeness, buildings with similar structural characteristics were preferred. All buildings constructed before 2000 were four-story structures, while those built between 2000 and 2011 were predominantly four-story, with one five-story building. The presence of basements was also recorded, as this affects foundation type and waste composition. Prior to demolition, household items and personal belongings were removed by the owners. As a result, the demolition process mainly involved the RC structural elements and roof components (Figure S2). Controlled demolition was carried out by contracted companies, and the excavated debris was transported to TSS (Figure S3). For each building, five debris piles unloaded from different trucks were randomly selected and numbered. From these, three piles per building were randomly chosen for characterization, resulting in a total of 27 piles (Figure S4). In addition, three debris piles were collected from different locations within the TSS (Figure S5). Overall, 30 mixed debris piles were collected and used for material characterization analysis.

Waste characterization was conducted in accordance with ASTM D5231–92 [35] to ensure homogeneous mixing and representative sampling. The waste was classified into eight categories: textiles, paper/cardboard, plastics, wood, metals/electronics, bulky items, iron, and debris. Each fraction was weighed to determine its mass percentage in the waste pile (Figure S6). Debris characterization was performed using samples collected from homogeneously mixed debris by applying the quartering method defined in ASTM D5231–92 [35]. A total of 10 tons of debris was analyzed. The material was spread on a clean surface, and large concrete pieces were hand-sorted. The remaining material was sieved through a 15 mm mesh. The fraction passing through the sieve was defined as sieved material, while the oversize fraction was hand-sorted. Debris was then classified into eight categories: glass, wood, autoclaved aerated concrete (AAC), brick/tile, ceramic, stone, concrete, and sieved material, and the mass percentages were determined (Figure S7).

2.1.3. Waste processing (crushing and sieving), aggregate classification and collection of samples

Debris (glass, wood, AAC, brick/tile, ceramic, stone, concrete, and sieved material) and sorted concrete was obtained during the characterization study for each building age group using the quartering method (Figure S7). Following the completion of the characterization studies, debris and concrete samples were subjected to mechanical crushing and sieving to be able to obtain RMA and RCA fractions respectively from the building groups for the laboratory analysis. Prior to crushing, the samples were placed into bulk bags with 1 ton capacity, and transported to the crushing facility (Figure S8-S11). At the facility, the materials were processed and separated into three particle size ranges: 0–5 mm, 5–12 mm, and 12–22 mm (Figure S12-S19). Following crushing and sieving, each material fraction was transferred into new, labeled bulk bags to prevent cross-contamination. The prepared samples were then transported to the laboratories where the experimental studies were conducted.

2.2. Laboratory analysis

The laboratory analysis were conducted to test the physical, mechanical, geotechnical and durability behavior of materials ensuring consistency with the functional requirements of each application; road construction, cement production and concrete production. Applied tests and standard methods are given in Table 1.

For road construction step, physical properties and mechanical properties were tested via using %100 RMA and RCA with two fractions as coarse (5–22 mm) and fine (0–5 mm) particles. In Türkiye, the geotechnical requirements for materials to be used in road embankments, base and subbase layers are defined in the Turkish Highway Technical Specifications [36]. The physical properties of the RCA and associated fine materials were determined through a comprehensive set of standardized geotechnical tests in order to evaluate their suitability for use in pavement base and subbase layers. Relative density was determined in accordance with TS EN ISO 17892–3 [37] by establishing the maximum and minimum reference densities of the granular material and comparing these values with the measured in-place density, providing an indication of particle packing efficiency and compaction potential. The durability of the materials under environmental and mechanical actions was evaluated using Freeze-Thaw (F-T) Resistance test and Los Angeles (LA) Abrasion test. F-T Resistance was assessed by subjecting specimens to repeated cycles of freezing and thawing under controlled temperature conditions and subsequently determining mass

Table 1
Applied tests and corresponding standard methods.

Applied Test	Standard Method	Purpose of Tests
Relative Density[f, c]	TS EN ISO 17892–3 [37]	Base and subbase
γd max-standart[f, c] Wopt-standart[f, c] γd max-modified[f, c] Wopt- modified[f, c]	TS 1900–1 [39]	Base and subbase
Plastic Limit (PL), Liquid Limit (LL) Plasticity Index (PI)[f, c]		
Particle Density (ρa)[f, c, c1, c2]	TS EN 1097–6 [40]	Base and subbase, Concrete
Water Absorption (WA)[f, c, c1, c2]		Base and subbase, Concrete
Methylene Blue (MB) Index[f]	TS EN 933 – 9 [41]	Base and subbase, Cement
Sieve Analysis[f, c1, c2]	TS EN 933–1 [42]	Concrete
LA Abrasion (k)[f, c, c1, c2]	TS EN 1097–2 [38]	Base and subbase, Concrete
Freeze-Thraw (F-T) Resistance[f, c]	TS EN 1367–2 [43]	Base and subbase
California Bearing Ratio (CBR)[f, c]	ASTM D1883 [44]	Base and subbase
Flakiness Index (FI)[f, c]	TS EN 933–3 [45]	Base and subbase
Shape Index (SI)[f, c]	TS EN 933–4 [46]	Base and subbase
Friction Angle (ϕ)[f, c]	TS EN ISO 17892–9 [47]	Base and subbase
Cohesion Intercept (c)[f, c]	TS EN ISO 17892–10 [48]	Base and subbase
Low Level Permeability[f, c]	TS EN ISO 17892–11 [49]	Base and subbase
Total Sulfate Content[F]	TS EN 196–2 [50]	Cement
Total Organic Carbon (TOC)[F]	TS EN 13639 [51]	Cement
Alkali-Silica Reaction (ASR)$^{f, c1, c2}_{avg}$	ASTM C 1260–21 [52]	Concrete
Lightweight Organic Compounds[f, c1, c2]	TS EN 1744–1 [53]	Concrete
Soundness[f,c]	ASTM C88 [54]	Base and subbase
Org. Matter Content[f, c]	ASTM D 2974–20E1 [55]	Base and subbase
Clay Lumps and Friable Particles[f, c]	ASTM C142 [56]	Base and subbase

Note: [f]:Fine Particles (0–5 mm); [c]: Coarse Particles (5–22 mm) ([c1]= 5–12 mm) ([c2]= 12–22 mm)

loss, which reflects the susceptibility of the material to weathering. The LA Abrasion (TS EN 1097–2) [38] (k) was obtained by exposing aggregates to impact and abrasion in a rotating drum with steel balls, and the degree of degradation was quantified through post-test Sieve Analysis.

Particle shape and geometry were evaluated using the Flakiness Index (FI) and Shape Index (SI) tests, which provide insight into the angularity and elongation of particles and their potential influence on interlocking and load transfer behavior. The presence of deleterious materials was examined through the Determination of Clay Lumps and Friable Particles for both fine and coarse fractions by separating weak or disintegrable particles after conditioning in water. In addition, the Methylene Blue (MB) Index test was applied to the fine materials to assess clay contamination based on dye adsorption capacity, while Organic Matter Content was determined by mass loss on ignition to evaluate the presence of organic impurities that could adversely affect engineering performance.

The mechanical and hydraulic behavior of the materials was evaluated using laboratory tests commonly employed in pavement and geotechnical engineering applications. Standard and Modified Proctor compaction tests were carried out according to TS 1900–1 [39] by compacting specimens at different moisture contents under specified energy levels to determine the maximum dry unit weight ($\gamma d,max$) and the corresponding optimum moisture content (Wopt). These parameters were used to characterize compaction behavior and to establish target conditions for subsequent mechanical testing. Shear strength parameters were determined through triaxial compression and direct shear tests conducted under controlled stress conditions. The Friction Angle (ϕ) was obtained in accordance with TS EN ISO 17892–9 [47] from triaxial tests by subjecting cylindrical specimens to different confining pressures and loading them axially until failure, allowing the construction of Mohr–Coulomb failure envelopes. The Cohesion Intercept (c) was determined from direct shear tests by applying different normal stresses and measuring the peak shear resistance along a predefined shear plane. The load-bearing capacity of the materials was evaluated using the California Bearing Ratio (CBR) test, in which compacted specimens were penetrated at a constant rate and the measured resistance was compared with standard reference loads. This test provided an index parameter commonly used in the design of pavement base and subbase layers.

The hydraulic behavior of the materials was assessed through Low-Level Permeability tests using constant-head or falling-head permeameters, depending on the expected permeability range, enabling the determination of hydraulic conductivity (k). Furthermore, the consistency and classification characteristics of the fine fractions were evaluated through Atterberg limit tests, including the Liquid Limit (LL) and Plastic Limit (PL), from which the Plasticity Index (PI) was obtained in accordance with TS EN ISO 17892–12 [57].

To assess the performance of RCA in concrete production, a series of physical, durability, and reactivity tests were conducted. Particle density and Water Absorption (WA) were evaluated using standardized immersion and mass-volume equations to quantify aggregate porosity and its influence on effective water demand in concrete mixes. The LA Abrasion test was applied by subjecting aggregates to impact and abrasion in a rotating drum with steel balls to evaluate resistance to fragmentation. Potential average alkali-silica reactivity (ASR_{avg}) was investigated using the accelerated mortar-bar method, in which length changes of mortar specimens were monitored after exposure to a high-alkalinity environment. Furthermore, Sieve Analysis was carried out through mechanical sieving to determine particle size distribution, while Lightweight Organic Compounds were quantified by separating and weighing low-density particles that could adversely affect concrete durability and surface quality.

Characterization tests for cement production were conducted to evaluate the chemical suitability of recycled concrete waste. The MB Index (TS EN 933–9) [41] test was performed on fine samples to quantify the presence of clay minerals by measuring the adsorption capacity of MB dye under controlled stirring conditions. The Total Sulfate Content was determined through standardized chemical analysis by dissolving the sample and quantifying sulfate ions, allowing the SO_3 content to be calculated and assessed against relevant cement standards. In addition, Total Organic Carbon (TOC) content was measured according to TS EN 13639 [51] using a carbon analysis method based on controlled oxidation, in which the released CO_2 was quantified to determine the organic carbon fraction.

3. Results & discussion

The valorization potential of RMAs and RCAs derived from post-earthquake controlled DW in Türkiye was assessed for use in road base and subbase layers, as well as in concrete and cement production, based on their material properties. The aggregates were obtained from two main sources: (i) from controlled demolition of buildings constructed in different periods, and (ii) mixed debris collected from the Malatya TSS. This approach allowed an assessment of both material properties and construction-era effects on valorization potential. Sieve Analysis results for each group of samples is given in Table S1-S8.

3.1. Compliance of RMAs and RCAs as base and subbase layers for highway technical specifications

The suitability of RCAs and RMAs for use in road base and subbase layers was evaluated by comparing their physical, mechanical, and durability-related properties with the Turkish Highway Technical Specifications [36]. The Relative Density and Particle Density values of both RMA and RCA samples were within the typical range reported for aggregates used in road construction (Tables 2–3). The Relative Density (Gs) values of RMA ranged from 2.57 to 2.74, while RCA showed slightly higher values between 2.64 and 2.73, indicating the denser nature of concrete-based materials. For, Particle Density values of RCA ($\approx$ 2660–2700 kg/m^3) were slightly higher than some of the RMA ($\approx$ 2620–2680 kg/m^3), which is advantageous for load-bearing pavement layers. A significant difference was observed in WA. RMA samples showed high WA values ranging from 4.3% to 6.3%, substantially exceeding the commonly accepted 3% limit, particularly for TSS-derived materials. In contrast, RCA samples exhibited significantly lower WA values between 2.3% and 4.1%, with the lowest values observed in RCA obtained from Malatya TSS. MB Index values, which indicate clay content, remained low for RCA and RMA within the limits for both base and subbase layers. In contrast, coarse RCA and RMA samples showed relatively lower Contents of Clay Lumps and Friable Particles compared to fine RCA and RMA samples while results for both fractions varied across the building age groups. FI of all of the sample were compliant with the standard for base and subbase layers.

All RCA samples complied with the LA Abrasion limit ($\leq$35%) for base layers and remained well within the $\leq$ 45% limit for subbase layers. RMA samples also met the LA Abrasion criteria; however, pre-2000 RMA reached the upper limit (35%) threshold for base layer applications. F-T Resistance emerged as a critical differentiating factor. Only RCA sample derived from the 2000–2011 period was suitable for subbase layer limit ($\leq$25%), while the other samples exceeded both base and subbase limits. The majority of the samples complied with the 10% mass loss limit for soundness experiment. Only the RMA sample from the 2000–2011 period exceeded this threshold. The Friction Angle of RMA samples varied between 22.0° and 30.5°, while RCA samples showed a comparable but slightly narrower range of 18.3° to 24.1°. Although some RMA samples exhibited higher Friction Angles, RCA samples demonstrated more consistent shear strength behavior. Cohesion values were comparable between the two materials: with RMA ranging from 15.39 to 36.39 kPa and RCA ranging from 16.09 to 37.33 kPa, reflecting the heterogeneous nature of mixed aggregates. Compaction characteristics revealed that RCA generally achieved higher maximum dry densities ($\gamma d,max$). Under modified Proctor conditions, RCA values reached up to 21.49 kN/m^3 . In addition, RMA required higher optimum moisture

Table 2
Physical properties of RMAs and RCAs.

Parameter	Standard	Limit Value*	Unit	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018
				RMA**	RMA	RMA	RMA	RCA	RCA	RCA	RCA
Relative Density (Gs)	TS EN ISO 17892–3 [37]	-	-	2.65	2.74	2.57	2.63	2.73	2.71	2.67	2.69
Particle Density (ρa)[c]	TS EN 1097–6 [40]	-	kg/m^3	2.71	2.68	2.63	2.64	2.70	2.66	2.67	2.67
Water Absorption[c]	TS EN 1097–6 [40]	< 3–3.5	%	6.29	5.10	4.92	5.06	2.3	3.28	3.82	4.12
Grain Density (ρa)[f]	TS EN 1097–6 [40]	-	kg/m^3	2.59	2.52	2.46	2.61	2.62	2.52	2.47	2.62
Water Absorption[f]	TS EN 1097–6 [40]	< 3–3.5	%	22.6	18.97	14.69	16.06	9.3	6.73	13.71	12.54
F-T Resistance	TS EN 1367–2 [43]	< 20–25	% $MgSO_4$	28.3	29.9	29.1	28.9	27.9	28.2	22.3	27.1
LA Abrasion Coefficient (k)	TS EN 1097–2 [38]	< 35–45	%	27	35	34	34	33	34	32	31
Flakiness Index (FI)	TS EN 933–3 [45]	< 30–35	%	19.3	27.8	25.2	28	13.3	14.8	18.7	17.2
Shape Index (SI)	TS EN 933–4 [46]	-	%	8	16	15	12	3	3	9	7
Determination of Clay Lumps and Friable Particles[f]	ASTM C142 [56]	< 1–2	%	2.7	1.2	1.8	2.2	0.8	1.7	2.2	1.2
Determination of Clay Lumps and Friable Particles[c]	ASTM C142 [56]	< 1–2	%	1.1	1	1.3	0.8	1.1	0.8	1.1	0.9
Methylene Blue Index	TS EN 933–9 [41]	< 3–4	mg/g	0.75	1	1	2	0.75	0.75	0.75	0.75
Soundness[c]	ASTM C88 [54]	≤ 10	% Na_2SO_4	6.2	9.4	10.3	5.9	6.4	5.4	5.6	7.5
Soundness[f]	ASTM C88 [54]	≤ 10	% Na_2SO_4	0.7	0.7	0.4	0.5	0.7	0.3	0.2	0.4
Org. Matter Content	ASTM D 2974–20E1 [55]	-	-	1.48	2.39	2.79	3.17	1.19	1.03	1.07	1.26

Note: [f]: Fine Particles; [c]: Coarse Particles
*base and subbase materials lower limit considering Highway Technical Specification (GDH).
**Values represent the arithmetic mean of duplicate measurements. Statistical dispersion (SD) is not reported for these parameters due to the sample size (n = 2).

contents than RCA, confirming the higher water demand of mixed aggregates during field compaction. The CBR results strongly support the valorization of both materials. with RMA values ranging from 88% to 159%, while RCA values ranging from 100% to 125%. A CBR value exceeding 100% indicates that the tested material exhibits a bearing capacity superior to that of the standard crushed stone reference material. Pre-2000 RMA was the only sample that failed to comply with CBR limit for base layer. Particularly, RMA from the 2000–2011 period reached the highest CBR value (159%), and 2011–2018 RMA maintained a high CBR of 140.32%. These values significantly exceeded the minimum requirements for both base and subbase layers, demonstrating good load-bearing capacity in line with national specifications. All samples showed low permeability coefficients on the order of 1.27×10^{-5} to 2.34×10^{-5} m/s, which are suitable for drainage performance in pavement layers. Furthermore, all RMA and RCA samples were classified as Non-Plastic (NP), eliminating concerns related to shrinkage, swelling, or moisture-induced deformation.

WA and F-T Resistance emerged as the primary limiting factors. Coarse RCA from TSS and pre-2000 were compliant with subbase limits (≤3.5%), however, newer RCA and all RMA samples exceeded this threshold (Table 2). Similarly, in F-T resistance, only the RCA 2000–2011 (loss of 22.3%) met the ≤ 25% requirement. Although these results indicate vulnerability under severe frost conditions, they do not preclude valorization. MB Index remained low (0.75–2.0 mg/g), suggesting that the elevated "clay lumps" (0.8–2.7%) are a byproduct of crushed adhered mortar rather than harmful plastic clays. Despite these durability challenges, the CBR results strongly justify the utilization of these materials. Both RMA (88–159%) and RCA (100–125%) demonstrated stability superior to standard crushed stone references (100% CBR). Notably, the 2000–2011 RMA reached 159%, indicating potential for high-load applications (Table 3). Results showed that both RMA and RCA possess high valorization potential for road construction applications. RCAs, demonstrate lower WA, higher density, and more stable mechanical behavior, making it suitable for base layers. RMA, including materials sourced from the Malatya TSS, exhibits excellent bearing capacity despite higher WA and can be effectively utilized in base or subbase layers with controlled moisture and compaction practices. Accordingly, the geotechnical test results obtained in this study were compared with the limit values specified in GDH [36] for base and subbase materials. The comparison demonstrated that the tested materials generally comply with the required specification limits in terms of geotechnical performance. However, to mitigate the deficiencies in F-T resistance and WA observed at 100% replacement levels, different replacement ranges of 25%–75% can be an alternative pathway for valorization. This range was experimentally supported by Akbas and Iyisan [58] demonstrated that balanced NA-RCA blends, specifically 50% and 75% RCA mixtures, achieve the highest Resilient Modulus (M_R) values and superior resistance to plastic deformation under cyclic loading. Accordingly, the geotechnical comparison demonstrates that while a 100% replacement of NA may not meet all GDH [36] durability criteria, partial replacement rates (25%, 50%, and 75%) provide a balance between technical feasibility and large-scale environmental valorization of post-earthquake DW.

Table 3
Mechanical, geotechnical and durability-related properties of RMAs and RCAs.

Parameter	Standard	Limit Value*	Unit	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018
				RMA**	RMA	RMA	RMA	RCA	RCA	RCA	RCA
Friction Angle (φ)	TS EN ISO 17892–9 [47]	-	°	30.5	22.3	22.0	24.6	19.7	24.1	18.3	18.5
Cohesion Intercept (c)	TS EN ISO 17892–10 [48]	-	kPa	36.39	23.79	15.39	21.92	21.23	16.09	37.33	26.87
γd max-standart	TS 1900–1 [39]	-	kN/m^3	18.41	18.17	18.33	18.35	21.05	20.07	20.29	20.38
Wopt-standart	TS 1900–1 [39]	-	%	4.1	7.6	8.60	6.3	8.5	8.5	9.2	9.6
γd max-modified	TS 1900–1 [39]	-	kN/m^3	19.07	19.56	19.82	18.97	21.49	20.53	20.95	20.72
Wopt- modified	TS 1900–1 [39]	-	%	9.9	8.3	8.5	8.0	7.3	8.4	6.6	8.0
The California Bearing Ratio (CBR)	ASTM D1883 [44]	> 100 > 35	%	115.78	88.29	159.07	140.32	124.69	103.37	100.85	104.1
Low Level Permeability	TS EN ISO 17892–11 [49]	-	m/s	1.52×10^{-5}	1.63×10^{-5}	1.87×10^{-5}	1.27×10^{-5}	1.68×10^{-5}	2.34×10^{-5}	2.03×10^{-5}	1.39×10^{-5}
Plastic Limit (PL) Liquid Limit (LL) Plasticity Index (PI)	TS 1900–1 [39]	LL:NP-25 PI:NP-6	%	NP	NP	NP	NP	NP	NP	NP	NP

Note: NP: Non plastic
*base and subbase materials lower limit considering Highway Technical Specification (GDH).
**Values represent the arithmetic mean of duplicate measurements. Statistical dispersion (SD) is not reported for these parameters due to the sample size (n = 2).

3.2. Compliance of RMAs and RCAs for concrete standards

The valorization potential of RMA and RCA for concrete production was evaluated based on particle density, WA, LA Abrasion, ASR, fine content, and organic impurities (Tables 4–5). Particle Density values of RCA ranged from 2520 to 2660 kg/m^3, satisfying the minimum requirement of $>$ 2500 kg/m^3 for concrete aggregates. Notably, RCA derived from TSS exhibited the highest densities across all size fractions, reaching 2620 kg/m^3 (0–5 mm), 2640 kg/m^3 (5–12 mm), and 2660 kg/m^3 (12–22 mm). In contrast, RMA samples showed lower particle densities, ranging between 2330 and 2620 kg/m^3. RMAs exhibited the lower density values mostly below the threshold. This reduction is attributed to the presence of masonry-based components such as brick, tile, and ceramic, which limit the direct use of RMA in high-performance concretes.

A clear distinction between RCA and RMA was observed in terms of WA, which is a critical parameter for concrete mix design. The RCA samples showed absorption values between 2% and 4.6%, with the lowest values recorded for TSS RCA (2% and 2.4% for 12–22 mm and 5–12 mm), fully complying with the limit. RMA samples, exhibited significantly higher absorption values ranging from 4.8% to 12.1%, far exceeding the acceptable limit. These results indicate that RMA requires either pre-treatment or restricted use in non-structural concrete applications.

Los Angeles abrasion results further emphasized the superior mechanical performance of RCA. RCA abrasion values ranged from 20% to 28%, with the lowest values associated with newer buildings RCA (20%), indicating excellent resistance to mechanical degradation. These values are well within the acceptable 30–40% range for concrete aggregates. RMA abrasion values varied between 21% and 28%. Both RCA and RMA samples comply with the standards, these lower abrasion losses indicate higher durability and support their use in concrete subjected to mechanical stresses.

ASR expansion values for most of the RCA samples remained below 0.10%, classifying them as non-hazardous according to ASTM C1260. 2011–2018 12–22 mm RCA particularly higher ASR value (0.15%), indicating potential reactivity with cementitious systems. RMA samples showed slightly higher ASR values, ranging from 0.02% to 0.20%. While most RMA fractions remained within the non-hazardous or potentially hazardous range, RMA derived from the 2000–2011 period reached the upper threshold (0.20%), suggesting that careful ASR assessment is required before its use in concrete.

Sieve Analysis results indicated that fines content in RCA and RMA samples ranged from 5.9% to 14.2%, exceeding the 3–5% limit. Lightweight Organic Compound contents were consistently $<$ 0.01% for all RCA and RMA samples, confirming the absence of organic contamination that could negatively affect concrete performance.

The results show that RCA samples have high valorization potential for concrete production. Its high particle density, low WA, high LA Abrasion resistance, and negligible ASR reactivity make it suitable for both structural and non-structural concrete applications. In contrast, RMA shows limited but still relevant valorization potential, primarily constrained by high WA and lower density. It can be effectively utilized in non-structural concrete, especially after appropriate processing and quality control.

The findings confirm that material separation and seismic code based classification increase the recycling efficiency of DW. Therefore, RCA and RMA samples demonstrate strong potential for sustainable concrete production and for replacing NA.

3.3. Compliance of RMAs and RCAs for cement with recycled building materials standard

The suitability of RCA and RMA for cement production was evaluated in accordance with TS EN 197–6, which defines chemical and physical requirements for recycled construction materials intended for

Table 4
Test results and limit values for RMA.

Parameter	Standard	Limit Value	Unit	Malatya TSS			Before 2000			Between 2000 and 2011			Between 2011 and 2018		
				RMA*			RMA			RMA			RMA		
				0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm
Particle Density	TS EN 1097–6 [40]	> 2.5	mg/m^3	2.47 ± 0.29	2.49 ± 0.30	2.49 ± 0.22	2.62 ± 0.14	2.42 ± 0.18	2.4 ± 0.18	2.52 ± 0.11	2.33 ± 0.26	2.44 ± 0.06	2.45 ± 0.19	2.43 ± 0.26	2.42 ± 0.23
Water Absorption	TS EN 1097–6 [40]	< 3%	%	5.02 ± 0.28	4.9 ± 0.35	4.8 ± 0.62	12.1 ± 1.18	7.3 ± 0.33	7.6 ± 0.39	5.2 ± 0.32	10.22 ± 0.47	6 ± 0.47	6.7 ± 0.37	6.3 ± 0.54	6.9 ± 0.31
LA Abrasion	TS EN 1097–2 [38]	< 30–40%	%	-	23 ± 1.73	23 ± 1.73	-	28 ± 2.65	28 ± 2.65	-	27 ± 3.61	27 ± 3.61	-	21 ± 2.00	21 ± 2.00
ASR_{avg}	ASTM C 1260–21 [52]	< 0.1% Non-hazardous 0.1 <X < 0.2 Potentially hazardous X > 0.20 Hazardous aggregates	%	**0.02 ± 0.01 0.06 ± 0.02 0.16 ± 0.01	-	-	0.01 ± 0.005 0.03 ± 0.005 0.05 ± 0.01	-	-	0.03 ± 0 0.05 ± 0.005 0.20 ± 0	-	-	0.02 ± 0.008 0.06 ± 0.009 0.13 ± 0.005	-	-
Sieve analysis	TS EN 933–1 [42]	< 3–5%	%	5.9 ± 0.34	-	-	14.2 ± 1.71	-	-	11.4 ± 1.55	-	-	7.3 ± 0.52	-	-
Lightweight Organic Compounds	TS EN 1744–1 [53]	-	%	< %0.01 ± 0.0	-	-	< %0.01 ± 0.0	-	-	< %0.01 ± 0.0	-	-	< % 0.01 ± 0.0	-	-

*Values represent the mean of triplicate measurements (n = 3). Results are presented as mean ± standard deviation (SD).
** Values represent the 3rd, 7th and 14th day from top to down.

Table 5
Test results and limit values for RCA.

Parameter	Standard	Limit Value	Unit	Malatya TSS			Before 2000			Between 2000 and 2011			Between 2011 and 2018		
				RCA*			RCA			RCA			RCA		
				0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm	0–5 mm	5–12 mm	12–22 mm
Particle Density	TS EN 1097–6 [40]	> 2.5	mg/m^3	2.62 ± 0.17	2.64 ± 0.26	2.66 ± 0.16	2.62 ± 0.23	2.57 ± 0.06	2.58 ± 0.01	2.66 ± 0.14	2.61 ± 0.24	2.55 ± 0.35	2.54 ± 0.27	2.52 ± 0.16	2.54 ± 0.20
Water Absorption	TS EN 1097–6 [40]	< 3%	%	3.3 ± 0.27	2.4 ± 0.13	2.00 ± 0.17	3.5 ± 0.20	3.7 ± 0.37	3.3 ± 0.24	2.4 ± 0.16	2.9 ± 0.19	3.6 ± 0.28	4.6 ± 0.42	4.2 ± 0.34	3.7 ± 0.20
LA Abrasion	TS EN 1097–2 [38]	< 30–40%	%	-	28 ± 1.00	28 ± 1.00	-	22 ± 1.73	22 ± 1.73	-	22 ± 2.65	22 ± 2.65	-	20 ± 2.65	20 ± 2.65
ASR_{avg}	ASTM C 1260–21 [52]	< 0.1% Non-hazardous 0.1 <X < 0.2 Potentially hazardous X > 0.20 Hazardous aggregates	%	**0.01 ± 0 0.04 ± 0.01 0.07 ± 0.005	-	-	0.02 ± 0.008 0.03 ± 0.008 0.06 ± 0.005	-	-	0.01 ± 0 0.03 ± 0 0.06 ± 0.01	-	-	0.01 ± 0.005 0.07 ± 0.005 0.15 ± 0.01	-	-
Sieve analysis	TS EN 933–1 [42]	< 3–5%	%	9.5 ± 0.76	-	-	13.3 ± 1.64	-	-	12.0 ± 0.95	-	-	12.5 ± 1.45	-	-
Lightweight Organic Compounds	TS EN 1744–1 [53]	-	%	< %0.01 ± 0.0	-	-	< %0.01 ± 0.0	-	-	< %0.01 ± 0.0	-	-	< %0.01 ± 0.0	-	-

*Values represent the mean of triplicate measurements (n = 3). Results are presented as mean ± standard deviation (SD).
** Values represent the 3rd, 7th and 14th day results from top to down.

use as cement constituents (Table 6). The assessment focused on MB Index, Total Sulfate Content, and TOC, as these parameters directly affect cement hydration, durability, and long-term performance. According to TS EN 1097–6 [40], lower MB Index values are required to minimize adverse effects on cement hydration. RCA samples exhibited consistently low MB Index values ranging from 0.50 to 0.75 g, with most fractions clustering around 0.75 g, regardless of construction period. These values indicate a low clay content and high chemical compatibility with cementitious systems. In contrast, RMA samples showed significantly higher and more variable MB Index values. While TSS-derived RMA exhibited a relatively low MB Index of 0.75 g, RMA from 2000 to 2011 period reached values as high as 4.25 g, whereas pre-2000 samples reached 2.75 g. These elevated values reflect the presence of brick, tile, and ceramic fines, which increase clay-related reactivity and limit the direct use of RMA in cement production without further processing.

Total Sulfate Content is a critical parameter due to its influence on setting behavior and the risk of delayed ettringite formation. All RCA samples showed low sulfate contents between 0.20% and 0.54%, well below the 2% limit specified in TS EN 1097–6 [40] (Table 6). This demonstrates that RCA does not pose a sulfate-related durability risk when used in cement formulations. Similarly, RMA samples exhibited sulfate contents ranging from 0.26% to 0.51%, also remaining safely below the standard limit.

All samples' TOC content was significantly lower than the 0.8% limit specified in TS EN 1907–6. RCA samples showed very low TOC values between 0.01% and 0.11%, reflecting the inert nature of concrete-based materials and their suitability for clinker substitution or use as recycled cement constituents. On the other hand, RMA samples showed slightly higher TOC values (0.04–0.16%). While still within acceptable limits, these higher values suggest the presence of minor organic residues associated with mixed DW. Nevertheless, the measured TOC levels do not pose a technical barrier to cement production.

The results clearly indicate that RCA exhibits high valorization potential for cement production under the TS EN 1097–6 [40] framework. Its low MB Index, low sulfate content, and minimal organic contamination make RCA highly suitable for use as a recycled construction material in cement manufacturing, particularly when sourced from controlled demolition of newer buildings.

In contrast, RMA shows a more limited valorization potential. Although sulfate and TOC contents comply with TS EN 1097–6 [40] requirements, elevated and variable MB Index values indicate higher clay content or contamination. Consequently, the use of RMA in cement production should be restricted to controlled substitution ratios, or combined with pre-treatment methods such as washing, classification, or blending with RCA to ensure compliance with performance requirements. The findings demonstrate that within the scope of TS EN 197–6, RCA can be directly valorized, while RMA requires controlled use and additional quality management for its application in cement manufacturing processes.

3.4. Influence of seismic codes and source separation on aggregate quality

The classification of buildings into pre-2000, 2000–2011, and 2011–2018 represents more than only chronological building age; these periods signify distinct stages of technical and regulatory developments in Türkiye's construction industry. The observed improvements in RCA density and WA directly correlate with the progressively stricter mandates for concrete strength and material quality control introduced in each seismic code revision. This finding shows that seismic regulations act as a material quality filter, where newer buildings, designed for higher resilience, yield secondary aggregates that exhibit lower porosity and higher mechanical integrity. Consequently, the scientific value of this classification lies in its ability to streamline the source-separation process, allowing authorities to prioritize debris from specific regulatory eras for high-performance structural reuse. For instance, buildings constructed before 2000, between 2000 and 2011 and between 2011 and 2018, represent distinct phases of seismic regulation in Türkiye, characterized by progressively stricter requirements for material quality, concrete strength, reinforcement detailing, and construction control. This regulatory evolution is clearly reflected in the properties of the RCAs derived from these buildings.

Influence of building age on the performance of aggregates for road construction is reflected in the evolution of toughness and bearing capacity. For RCAs, the LA Abrasion loss improved from 34% (pre-2000) to 31% (2011–2018), indicating an approximately 9% increase in aggregate toughness as building design standards evolved (Table 2). The impact of the construction era is even more pronounced in the CBR results for RMAs; while materials from the pre-2000 era yielded a CBR of 88.29%, those from the 2000–2011 and 2011–2018 periods reached 159.07% and 140.32%, respectively. This represents an approximate 80% increase in bearing capacity for materials sourced from buildings constructed under more stringent seismic regulations. Furthermore, the Relative Density of RMAs showed a shift from 2.74 (pre-2000) to a more consistent range in newer periods, facilitating better compaction control in the field.

Aggregates intended for concrete production reveal a strong correlation between the seismic-code era and the reduction of deleterious physical properties. The WA of coarse RCA (12–22 mm), a critical indicator of adhered mortar volume, exhibited a quantitative decrease from 4.6% in the pre-2000 period to 2.5% in the 2011–2018 (Table 5). This 45% reduction in porosity directly correlates with the higher concrete strength classes mandated by modern Turkish seismic codes, which produce denser and less permeable recycled products. Concurrently, the Particle Density of these aggregates improved from 2.52 Mg/m^3 to 2.66 Mg/m^3 , significantly exceeding the minimum requirement for structural concrete. Mechanical durability also followed this trend, with LA Abrasion losses for RCAs dropping from 28% (pre-2000) to 20% (2011–2018), providing a quantitative confirmation of the superior aggregate integrity found in newer structural debris (Table 5).

The suitability of recycled building materials for cement manufacturing indicates a decline in chemical reactivity and organic impurities across construction eras. The MB index showed a 33%

Table 6
Requirements for recycled building materials usage in cement.

Parameter	Standard	Limit Value	Unit	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018	Malatya TSS	Before 2000	Between 2000 and 2011	Between 2011 and 2018
				RMA*	RMA	RMA	RMA	RCA	RCA	RCA	RCA
MB Index	TS EN 933–9 [41]	< 1.2 g	g	0.75	2.75	4.25	2.25	0.75	0.75	0.75	0.5
Total Sulfate Content	TS EN 196–2 [50]	< 2%	%	0.34	0.26	0.51	0.36	0.23	0.28	0.20	0.21
TOC	TS EN 13639 [51]	< 0.8%	%	0.12	0.04	0.16	0.13	0.03	0.11	0.01	0.04

* Values represent the arithmetic mean of duplicate measurements. Statistical dispersion (SD) is not reported for these parameters due to the sample size (n = 2).

improvement, decreasing from 0.75 mg/g (pre-2000) to 0.50 mg/g (2011–2018) for RCA fractions. This reduction indicates a higher degree of material purity in newer DW streams, thereby making them more compatible with cementitious systems. Additionally, the TOC values for RCAs were exceptionally low, reaching as low as 0.01% for modern cohorts, which is well within the 0.8% limit specified by TS EN 1097–6 (Table 6). These indicators demonstrate that while all seismic eras meet the minimum standard requirements, aggregates derived from modern regulatory frameworks offer a significantly more stable and chemically inert profile for clinker substitution.

Across all datasets, RCA quality shows an improvement as building age decreases. This trend indicates that newer seismic codes, which mandate higher concrete classes, improved mix designs, and stricter quality control, directly effects into higher-quality RCA with higher performance for road construction, concrete production, and cement manufacturing. In contrast, RCA derived from pre-2000 buildings showed relatively lower densities, higher absorption, and more variable mechanical behavior, reflecting the lower concrete strength classes and less stringent construction practices permitted under earlier seismic regulations.

While the influence of seismic code evolution is evident for RCA, its effect on RMA is more limited due to the inherently heterogeneous composition of mixed DW. This indicates that although modern seismic codes enhance the quality of the concrete fraction within RMA, they cannot fully overcome the limitations due to the material fraction of non-concrete constituents.

The MB Index values for RMA exhibited significant variability across the seismic-code eras, reaching up to 2.0 mg/g in the buildings between 2011 and 2018 (Table 2). Although these values are within the permissible limits for road construction, their fluctuation suggests a high sensitivity to the proportion of non-concrete constituents, such as masonry and old mortar [12]. To ensure long-term performance and minimize the risk of moisture-induced instability, two primary strategies can be applied. First, controlled substitution and blending, which are essential to counteract the high variability of active fines in RMAs [58]. Experimental findings suggest that blending NA with RA's in a %0% ratio can significantly enhance the resilient modulus (M_R) and provide a buffer against the high WA and MB activity of pure recycled streams. Second, pre-treatment strategies, through which the quality of RMAs can be significantly improved using specialized methods. Mechanical pre-treatments, such as grinding or scrubbing, are effective in removing the weak adhered mortar that often carries active fines. Furthermore, chemical treatments (e.g., acid washing) or surface coatings using SF slurry have been shown to clog micro-pores and reduce the permeability of the recycled matrix. Such treatments not only stabilize the MB Index values but also improve the ITZ, leading to enhanced mechanical strength and durability.

To mitigate the inherent variability and high WA of RMAs and RCAs advanced pre-treatment strategies are essential for achieving consistent material quality. Surface pre-treatment using SF slurry coating has emerged as a highly effective method for refining the pore structure of the adhered mortar and increasing the density of the ITZ [12]. As demonstrated by Sasanipour and Aslani [59], this coating process significantly reduces chloride ion penetration and increases electrical resistivity by filling micro-cracks within the recycled matrix. Such treatments enhance the overall durability index, providing a robust pathway for the structural use of heterogeneous DW. Comparative research by Kazmi et al. [60] indicates that mechanical grinding can improve the stiffness of RCA by 30% by physically removing the porous adhered mortar. Furthermore, acetic acid immersion offers a chemical pathway to dissolve weak mortar bonds, potentially increasing the modulus of elasticity by up to 29%. Integrating these pre-treatment protocols, especially for heterogeneous post-earthquake waste streams, can transforms low-grade debris into high-performance secondary resources, effectively stabilizing the fluctuating MB Index values and meeting the durability requirements for base and subbase layers. As a result, RMA remains more suitable for road subbase layers, blended applications, or controlled use in cement production rather than high-performance concrete. Materials sourced from the Malatya TSS represent a mixture of debris originating from buildings constructed under different seismic codes and demolition conditions. Consequently, TSS-derived RMA and RCA generally shows variability in physical, mechanical, and chemical properties.

The comparison between TSS materials and aggregates obtained from controlled demolition highlights the importance of material separation at the source, particularly, in post-earthquake waste management scenarios.

The combined results clearly demonstrate that the evolution of seismic codes in Türkiye has an impact on the quality of RAs, particularly RCAs. Based on the particularly high CBR values and low LA Abrasion losses, recycled materials derived from newer buildings designed and constructed under modern seismic regulations exhibit higher valorization potential in road base and subbase applications, concrete production, and use as cement additives.

Collectively, the literature and the findings of this study indicate that the valorization potential of RCAs and RMAs are strongly application- and standard-dependent. Joseph et al. [61] stated that RAs have higher WA compared to NAs. For this reason, its heterogeneous nature constitutes a key limitation for reuse in new construction materials. The high WA of RAs is related to the presence of old mortar [62]. NA have WA values between 0.5% and 1.5% while RAs WA may reach values of up to 12% [63,64]. In addition, Peng et al. [65] showed experimentally that the WA of RCA was much higher than NA. After removing the attached mortar, the WA of RCA decreased from 4.07% to 2.89% and from 7.89% to 2.77%, respectively. Pedro et al. [66] stated that the density of RCA is lower than that of NA due to the presence of adhered cement mortar. Brito and Saikia [67] reported that the density of RCA typically ranges between 2200 and 2600 kg/m^3 . The different size fractions (fine and coarse) can show a different density due to the adhered mortar ratio [68]. The density values are generally lower than RCA, since RMA composed of crushed concrete and masonry rubble [69]. Agrela et al. [70] evaluated NAs and RMAs, reporting that soluble sulfate contents were below the limits and the Total Sulfate Content did not exceed the 1% limit for pavement structural layer materials.

Mehrjardi et al. [71] evaluated the physical and mechanical properties of CDW materials in comparison with NAs for specifications of subbase materials. Durability-related properties further support the feasibility of CDW use. LA Abrasion losses of RCA and mixed CDW were reported to be below the commonly accepted threshold of 40% for subbase layers (AASHTO T 96 [72]). In terms of load-bearing performance, CBR values obtained for RCA and mixed CDW generally met or exceeded minimum subbase requirements. Akbas et al. [24] reported that RCA-based unbound layers exhibited CBR values sufficient for low- to medium-traffic roads, particularly when proper compaction was applied. Long-term performance observations further indicate that RCA layers may benefit from self-cementing effects due to residual anhydrate cement particles, leading to gradual increases in stiffness and bearing capacity over time [13]. Molenaar and van Niekerk [73] showed that the mechanical performance of crushed concrete and masonry used in unbound base layers is influenced by composition, gradation, and compaction, with the degree of compaction being the most critical and practically controllable factor.

The incorporation of RCAs affected by ASR can initiate the expansion reaction in new RCA concrete [62]. The relatively low ASR expansion values obtained for most RCA and RMA samples are consistent with the findings of Zhu et al. [74], who reported expansion values below the ASTM C1260 limit of 0.10% for glass-containing aggregates. In contrast, the higher expansion observed in specific RCA and RMA fractions (up to 0.15–0.20%) remains significantly lower than the values reported for highly reactive NA (0.27–0.32%) under aggressive exposure conditions, as documented by Abbas et al. [75] indicating a comparatively moderate ASR risk but highlighting the need for material-specific assessment.

The reviewed studies demonstrate that CDW-derived aggregates, particularly RCA, can meet standard technical criteria for use in road base and subbase layers, provided that material selection, processing, and quality control are carefully managed. Their application is especially suitable for subbase layers and low-traffic road infrastructures, offering significant environmental benefits through the reduction of NAs consumption and landfill disposal.

Overall, the findings underscore that the feasibility of utilizing RA is highly application-dependent, requiring a careful alignment between material properties and end-use requirements. High-quality RCA can be effectively utilized in concrete and road construction applications under controlled conditions, whereas RMA generally requires more conservative routing due to compositional variability and contamination risks. This distinction is particularly relevant for post-earthquake DW, where time constraints and limited pre-sorting exacerbate material heterogeneity.

The results emphasize the need for performance-based and application-oriented valorization strategies, rather than uniform recycling approaches. By integrating field-derived material characteristics with laboratory-based performance testing, this study contributes to the development of realistic and safe valorization pathways for RAs from DW.

4. Valorization and Application Potential of RCAs and RMAs

The comprehensive assessment of RAs derived from post-earthquake DW reveals distinct valorization pathways that are highly dependent on material composition, source characteristics, and the evolution of seismic codes. A clear distinction exists between RCA and RMA. RCAs, particularly, performed higher physical and mechanical consistency due to their lower porosity and higher density. In contrast, RMAs were characterized by high heterogeneity resulting from the presence of masonry-based constituents like brick and ceramic. This composition were increased water demand and limits performance in high-strength systems, often requiring more conservative routing in infrastructure projects compared to concrete-rich waste streams. The quality of recycled materials was linked to the seismic code under which the related structure was constructed. This regulatory evolution was served as a material quality filter; buildings designed under modern seismic regulations (post-2011) yield higher quality RCAs that are technically comparable to NAs. Conversely, materials sourced from older periods (pre-2000) or unsorted TSS showed variability, emphasizing the critical role of source-based separation in post-disaster waste management. The valorization potential of these materials was strongly application-dependent, requiring a careful alignment between material properties and end-use requirements. High-grade RCAs from controlled demolition were prioritized for structural applications due to their high particle density and resistance to mechanical degradation, such as LA Abrasion. Both RCA and RMA were demonstrated high CBR and shear strength consistency, making them highly suitable for road base layers. For subbase applications and lower-traffic infrastructure, RMAs and TSS materials provide adequate drainage performance despite their higher WA. High-grade RCA was preferred additive in cement production owing to its low chemical reactivity (MB Index values), low sulfate content, and minimal organic impurities, aligning with standards.

To overcome the inherent limitations of 100% replacement, such as reduced stiffness and higher porosity, a controlled substitution range of 25%-75% is recommended to ensure structural integrity. Furthermore, advanced pre-treatment methods can significantly elevate material quality. Surface-level enhancements, such as SF slurry coatings, effectively refine the pore structure and reduce permeability. More fundamental matrix improvements can be achieved through mechanical grinding to remove weak adhered mortar or chemical treatments like acetic acid immersion, which have been shown to substantially increase the stiffness and durability of RA systems. These strategies can transform heterogeneous disaster waste into standardized, high-performance secondary resources for the circular economy.

5. Conclusion

This study investigated the valorization potential of RCA and RMA obtained from post-earthquake controlled DW in Türkiye, with a focus on their applicability in road construction, concrete and cement production. Through the evaluation a wide range of physical, mechanical, durability-related, and chemical properties against relevant standards, the study provides a comprehensive overview of how these materials can be valorized. The results show that DW material quality is closely related to construction period, reflecting changes in seismic regulations. More recent buildings generally produced higher-quality RCA with lower contamination levels, while RMA showed greater variability due to its heterogeneous nature. Compared to RCA, the use of RMA is more limited. Although RMA from newer buildings showed some improvement, its heterogeneous composition, particularly the presence of masonry materials, led to higher WA, lower resistance to F-T action, and increased clay-related indicators. These characteristics limit its direct use for road works and applications in concrete and cement production. Nevertheless, with appropriate processing and quality control, RMA can still play an important role in reducing waste and conserving natural resources.

Overall, the results emphasize that building design and construction directly influence the recyclability of materials after demolition. Controlled demolition practices informed by building age and seismic code history can improve the quality and reuse potential of RA. By prioritizing high-quality RCA and managing RMA through controlled valorization strategies, demolition debris can be transformed from a disposal challenge into a valuable resource stream. This approach supports sustainable infrastructure development and contributes to the broader transition toward circular construction practices in Türkiye. Additionally, pre-treatment and separation methods should be optimized to reduce the heterogeneity of post-earthquake DW and increase its quality consistency. A more comprehensive assessment of the economic and environmental viability of large-scale implementation in Türkiye could be achieved by incorporating LCA and techno-economic analysis into valorization strategies.

CRediT authorship contribution statement

Kadir Ozcelik: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Serra Selin Ovez:** Writing – review & editing, Formal analysis, Data curation. **Kadriye Elif Maçin:** Writing – review & editing, Supervision. **Merve Akbas Kaplan:** Writing – review & editing, Supervision, Methodology. **Caglar Goksu:** Writing – review & editing, Supervision, Methodology. **Yilmaz Akkaya:** Writing – review & editing, Supervision, Methodology. **Recep Iyisan:** Supervision. **Osman Atilla Arikan:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT and Gemini in order to enhance clarity and fluency of selected passages. After using these tools, the authors reviewed and edited the content as needed for the content of the article.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.conbuildmat.2026.146613.

Data availability

Data will be made available on request.

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