Design of Concrete Made with Recycled Brick Waste and Its Environmental Performance

Ivan Janotka 1,*, Pavel Martauz 2 and Michal Bačuvčík 1

1 Building Testing and Research Institute (TSÚS), Studená 3, 821 01 Bratislava, Slovakia; bacuvcik@tsus.sk
2 Považská Cementáreň Cement Plant (PCLA), Ulica Janka Kráľa, 018 63 Ladce, Slovakia; martauz.p@pcla.sk
* Correspondence: janotka@tsus.sk; Tel.: +00421-918-943-972

Abstract: In addition to the known uses of natural clays, less publication attention has been paid to clays returned to the production process. Industrially recovered natural clays such as bricks, tiles, sanitary ceramics, ceramic roofing tiles, etc., are applicable in building materials based on concrete as an artificial recycled aggregate or as a pozzolanic type II addition. In this way, the building products with higher added value are obtained from the originally landfilled waste. This paper details the research process of introducing concrete with recycled brick waste (RBW) up to the application output. The emphasis is placed on using a RBW brash as a partial replacement for natural aggregates and evaluating an RBW powder as a type II addition for use in concrete. A set of the results for an RBW is reported by the following: (a) an artificial RBW fine aggregate meets the required standardized parameters for use in industrially made concrete, (b) a RBW powder is suitable for use in concrete as industrially made type II addition TERRAMENT showing the same pozzolanic reactivity as a well-known and broadly used pozzolan-fly ash, and (c) such an RBW as aggregate and as powder are, therefore, suitable for the production of industrially made TRITECH Eco-designed ready-mixed concrete.

Keywords: industrially processed clays; recycled brick waste; aggregate; addition; concrete

1. Introduction

It is impossible to use natural clays in concrete due to their intensive water absorption, associated deterioration of performance, and obvious volume changes associated with outer humidity changes (e.g., wet–dry outer environment). This disadvantage is eliminated in the case of industrially recovered natural clays, which are applied in concrete either as an artificial aggregate or as a pozzolanic type II addition. In this way, space is open for the active use of industrially processed natural clays in concrete with the effective recovery of landfilled construction and demolition (C&D) waste into a material with a higher added value. Such treated clays can be homogenized with recycled concrete waste to be recycled together to gain a material usable again in the construction practice. The research to date has shown the evolution of preparing eco-friendly mortar with various fineness levels and replacement ratios of RBW coming from C&D waste. Recycled fine aggregates and waste powders can be ground into ultrafine powders, defined as recycled powders for effective utilization of C&D waste. However, the performance of recycled powders relies on their sources, the complex components, which hinder their application [1]. Due to the pozzolanic activity and filler effect of RBW, the use of high-fineness RBW improves the hydration degree and refines the pore network of cementitious materials; the pozzolanic reactivity of RBW increases with an increasing fineness [2]. The results showed that the irregular and rough shapes of RBW required higher water consumption to achieve a standard consistency of a cement-based paste. The higher alkali-content and lower content of SO₃ of recycled powder contributed to the higher heat evolution rates of the pastes with RBW in the first 30 min, but the pastes with recycled powder exhibited lower cumulative hydration heats than pure cement after 1 day. The additional use of RBW decreased the flowability, density,

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and strength of mortar. Incorporation of recycled fine aggregates at 15 wt % does not negatively affect the mechanical performance of the mortars. The mixed brick and clay brick powders had a relatively positive impact on the mechanical properties of mortar also at later ages. The maximum reduction of strength was about 20 wt %. The addition of RBW reduces the number of hydration products. Incorporating RBW increases the water demand and decreases the slump of the prepared mixture. The incorporation of RBW results in a decrease in drying shrinkage as well. When the RBW fineness is higher than that of the cement, the compressive strength increases with increasing RBW content up to 15 wt %, and the maximum activity index of RBW is approximately 90%. The flexural strength decreases linearly with increasing RBW content. The flexural strength of mortar with high-fineness RBW is higher than that of mortar with low-fineness RBW [1,3–7]. The use of RBW decreases the resulting expansion due to the alkali-silica/aggregate reaction (ASR).

The CO$_2$-curing treatment is more suitable for RBW modification because RBW absorbs the CO$_2$ gas while also improving the properties of the prepared concrete, and thus, is more eco-friendly. RBW-containing concrete has a lower preparation cost than plain concrete, and the energy consumption and CO$_2$ emission of concrete preparation decrease with an RBW incorporation. The use of RBW in cement concrete products shows good recycling, economic and environmental benefits [8]. The results show that such a replacement reduces the chloride migration, but, contrary, increases water absorption, water sorptivity, drying shrinkage, and carbonation. The above-mentioned properties can be minimized by the water content reduction using a superplasticizer. The pore structure of RBW-containing concrete deteriorates with increased cement replacement because of the RBW porous structure. Contrary, due to the pozzolanic reactivity of RBW, the Ca(OH)$_2$ crystals in the formed binding hydrate phase are consumed to generate to a larger extent gel-like hydration products (C-S-H and C-A-H). This, in the final effect, results in a denser interfacial transition zone and enhanced adhesion between the RBW and the cement matrix [9]. It was also revealed that the recycled concretes incorporating ceramic waste as secondary clay materials have a comparable performance level to the one exhibited by the conventional concrete at 28 days, in part due to their pozzolanic characteristics, but also due to a lower effective water–cement ratio [10]. The application of recycled clay brick in concrete can solve the disposal problem of demolished solid waste. There are two main utilization purposes of such material: (1) recycled clay brick powder has a pozzolanic reactivity and can be used as a cement replacement, and (2) recycled clay brick aggregate can attain suitable strength and can be used in the production of medium- and low-strength concrete [11]. A case study conducted to verify the applicability of RBW in Shenzhen of China subjected to massive urban renewal pressure shows the following types of recyclable products: 18.41 million tons of recyclable bricks, 7.02 million tons of mortar, 28.36 million tons of aggregate, and 4.16 million tons of lightweight wallboard [12]. At present, 200,000 tons annually of industrially processed RBW waste with recovered natural clays and recycled concrete content of approx. 51:49% by weight are manufactured by Hasenöhrl GmbH, St. Panthaleon (Austria) for reuse in TRITECH Eco-designed ready-mixed concrete C 25/30 strength class.

Today’s state-of-the-art issues of using recycled material also include other products, such as beer green glass, waste tile, asphalt [13], glass as fine aggregate [14] and ceramic [15] waste. Each waste, by its presence in concrete, affects its properties. Attention is focused mainly on strength characteristics and long-term service life than concrete made only of natural aggregates.

This paper also aims to show the feasibility of using a recycled brick waste as a partial alternative of natural fine aggregate and a fine powder in the Eco-concrete production (TRITECH) [16] and as the fine powder as pozzolanic type II addition (TERRAMENT) [17] for use in concrete. Unlike existing laboratory experiments and relevant findings to date, this paper upgrades the existing knowledge with information about the complete research process necessary to implement recycled brick waste in practice as the certified construction products.
2. Research Significance

The related research was focused on the examination of the suitability of such recycled brick waste in concrete. The RBW substitutes a part of 0/4 mm fraction of natural aggregate (further abbreviated as NA) with equivalent grain-sized 0/4 mm (RBW-0/4) and/or cement as a powder of the specific surface area 300 m²/kg (RBW-P300) and 500 m²/kg (RBW-P500). The utility properties of RBW as an aggregate and those of NA of 0/32 mm size and as a blend of 0/32 mm NA and RBW 0/4 mm (NA + RWB blend) according to the specific concrete mixture composition were tested in compliance with the requirements of STN EN 13055-1 [18] and STN EN 12620 + A1 [19]. As the subject of innovative know-how, the mentioned concrete mixture compositions are confidential. The RBW powder was alone studied as an innovative type II addition for use in concrete, partially replacing the cement. Pozzolanic reactivity according to the Frattini test [20] and the suitability of an RBW powder properties, as specified in STN EN 450-1 [21] defining the chemical, physical, and quality control requirements for fly ash used as type II addition following STN EN 206 + A1 [22], were determined. The article introduces the methodological and experimental process of technology-oriented investigation with the final output in two innovative concrete products into building practice. The industrial outcome is the TRITECH Eco-designed ready-mixed concrete C 25/30 strength class and the type II addition TERRAMENT for use in concrete [23,24].

3. Experimental Procedure

Materials

CEM II/B-S 42.5 N cement (producer: Považská cementáreň, a.s., cement plant, Ladce, Slovakia abbreviated as PCLA) and natural aggregate (supplier: Hasenöhrl GmbH, Sankt Pantaleon, Austria) of 0/4, 4/8, 8/16, and 16/32 mm (abbreviated as NA) were used in the reference concrete (REF-1). In the experimental concrete (TRITECH as EXP-1), the 0/4 mm RBW (manufactured: Hasenöhrl GmbH, Sankt Pantaleon, Austria) partially replaced the 0/4 mm NA and 10 wt % of the cement was substituted by the RBW powder. The EXP-2 concrete for k-value estimation was prepared with the 10 wt % cement replacement by the RBW powder differing in specific surface areas 300 m²/kg and 500 m²/kg and only a natural aggregate (TERRAMENT). The REF-2 concrete mixture contained 100 wt % of the cement. The chemical admixtures SIKA 4025 and SIKA 4035 (SIKA Slovensko, s.r.o., Bratislava, Slovakia) were used to manufacture individual concrete types.

4. Methodology

4.1. Casting and Testing

The consistency of fresh concretes was determined either by the flow-table or the slump-test methods [25]. After demolding (24 h), concrete specimens as 150 mm cubes and (100 × 100 × 400) mm prisms were stored in water at (20 ± 1) °C. Utility properties were determined at 28 and 90 days of concrete age. The k-value for the RBW powder with a specific surface area of 300 m²/kg and 500 m²/kg at the 10 wt % cement was substituted by the RBW powder. The EXP-2 concrete for k-value estimation was prepared with the 10 wt % cement replacement by the RBW powder differing in specific surface areas 300 m²/kg and 500 m²/kg and only a natural aggregate (TERRAMENT). The REF-2 concrete mixture contained 100 wt % of the cement. The chemical admixtures SIKA 4025 and SIKA 4035 (SIKA Slovensko, s.r.o., Bratislava, Slovakia) were used to manufacture individual concrete types.

4.2. Verification of RBW Powder as the Active Pozzolan

The RBW powder was tested on a pozzolanic reactivity by Frattini test performed on two sets of the samples with a specific surface area of 300 m²/kg and 500 m²/kg. The Frattini test consists of mixing 1 g RBW with 75 mL of saturated lime solution at (40 ± 1) °C for 1, 7, and 28 days. At the end of each period, CaO-remaining concentrations in the
solution are measured according to STN EN 196-5 [32] and re-calculated to mass percentage consumption of CaO by the RBW.

4.3. Applicability of RBW Powder as a Pozzolanic Type II Addition

The RBW properties were determined according to STN EN 450-1, which complies with STN EN 206 + A1. This closest standard related to fly ash was chosen to evaluate the RBW powder as a pozzolanic addition, as the tested RBW does not have its standard. The RBW powder may not meet the parameters required for fly ash; these serve as indicators of the quality of a pozzolan under consideration.

4.4. Performance of Aggregates

Relevant aggregate tests according to the EN 12620 +A1 requirements were carried out on three aggregate systems: fine RBW with declared grading: D ≤ 4 mm, NA having declared grading: D between 0 and 32 mm, and a blend of NA and RBW, in which a part of NA was substituted by fine RBW 0/4 mm in the experimental concrete (EXP-1) according to the specified concrete mixture composition. The aggregates were tested as-received from the producer. According to STN EN 13055-1, density in the dried state did not exceed 2000 kg/m$^3$ (2.00 Mg/m$^3$) or whose bulk density of loose aggregate did not exceed 1200 kg/m$^3$ (1.20 Mg/m$^3$). Concerning the values of bulk density of loose aggregate 1.20 Mg/m$^3$ and grain density of dried aggregate 2.12 Mg/m$^3$, fine RBW 0/4 mm was included in the category of common aggregates with property criteria according to STN EN 12620 + A1 and not as a light aggregate according to STN EN 13055-1.

Table 1 provides the list of verified properties necessary for the certification process and relevant standards, as well as the tests needed to verify the properties of RBW 0/4 mm, NA 0/32 mm and a (NA + RBW 0/32 mm) blend applied in the TRITECH ecotechnology concrete.

| Property Requirement for Addition | Test Rule/Standard |
|----------------------------------|--------------------|
| Ignition loss                    | STN EN 196-2 [33]  |
| Fineness                         | STN EN 451-2 [34]  |
| Free calcium oxide content       | STN EN 450-1 [19]  |
| Carbon dioxide content           | STN EN 196-2 [33]  |
| Calcium oxide content            | STN EN 196-2 [33]  |
| Content of chlorides             | STN EN 196-2 [33]  |
| Sulfur trioxide content          | STN EN 196-2 [33]  |
| Specific grain density           | STN EN 196-6 [35]  |
| Activity index after 28 days and 90 days | STN EN 196-1 [36]  |
| Soundness                        | STN EN 196-3 [37]  |
| Sample decomposition and the contents of (MgO, CaO, SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$) | STN EN 196-2 [33]  |
| Total content of (silicon + aluminum + ferric) oxides | STN EN 196-2 [33]  |
| Active silicon-oxide             | STN EN 196-2 [33]  |
| Alkali content                   | STN EN 196-2 [33]  |
| Magnesium oxide content          | STN EN 196-2 [33]  |
| Initial setting (a mixture of 25% RBW powder and 75% cement by weight) | STN EN 196-3 [36]  |

| Property Requirement for Aggregate [19] | Test Rule/Standard |
|-----------------------------------------|--------------------|
| Content of natural radionuclides        | STN EN 12620 + A1  |
| Content of hazardous substances         | STN EN 12620 + A1  |
| Content of water-soluble and acid-soluble chlorides | STN EN 12620 + A1  |
| Content of acid-soluble sulfates        | STN EN 12620 + A1  |
Table 1. Cont.

| Property Requirement for Aggregate [19] | Test Rule/Standard |
|----------------------------------------|--------------------|
| Total sulfur content and humus content  | STN EN 12620 + A1  |
| Organic impurities (constituents that change setting and hardening velocity of concrete) | STN EN 12620 + A1 |
| Granularity and fine grain content      | STN EN 12620 + A1  |
| Bulk density (both of loose aggregate and agglomerated aggregate) | STN EN 12620 + A1 |
| Volume stability–shrinkage by drying    | STN EN 12620 + A1  |
| Alkali–silica reaction                  | STN EN 12620 + A1  |

4.5. Performance of Cement and Superplasticizer

The cement properties were analyzed according to EN 197-1 [38] and STN 72 1179 [39], and those of superplasticizer according to EN 934-2 + A1 [40]. The required range of tests is reported in Table 2.

Table 2. Range of standard cement tests and chemical admixtures.

| Property Requirement | Test Rule |
|----------------------|-----------|
| Cement               |           |
| Initial and final setting | STN EN 196-3 + A1 [37] |
| Flexural and compressive strength after 2, 7 and 28 days | STN EN 196-1 [36] |
| Sodium oxide equivalent | STN EN 196-2 [33] |
| Specific gravity | STN 72 2113 [41] |
| Specific surface area | STN EN 196-6 [34] |
| Superplasticizer      |           |
| Sodium oxide equivalent | STN EN 480-12 [42] |
| Content of chlorides | STN EN 480-10 [43] |

4.6. Performance of Concrete

The REF-1 concrete and EXP-1 concrete made with RBW as a 0/4 mm aggregate and as a powder was tested according to valid European (STN EN) and Slovak (STN) standards. The necessary standard tests for the certification process are revealed in Table 3.

Table 3. Range of standard tests for fresh and hardened concrete.

| Property of Concrete | Test Rule |
|----------------------|-----------|
| Consistency of fresh concrete—flow table test | STN EN 12350-5 [44] |
| Volume density of fresh concrete | STN EN 12350-6 [45] |
| Air content of fresh concrete | STN EN 12350-7 [46] |
| Loss of workability of fresh concrete | STN EN 12350-5 [44] |
| Cube compressive strength after 28 and 90 days | STN EN 12390-3 [26] |
| Dynamic modulus of elasticity after 28 and 90 days | STN 73 1371 [47] |
| Young’s modulus of elasticity and compressive strength on the prism edges after 28 and 90 days | STN ISO 6784 [48] |
| Flexural strength after 28 and 90 days | STN EN 12390-5 [49] |
| Suction capacity after 28 and 90 days | STN 73 1316 [28] |
| Resistance to water penetration under pressure after 28 days | STN EN 12390-8 [29] |
| Resistance to freezing and thawing—50 cycles after 28 and 90 days | STN 73 1322 [50] |
| Resistance of cement concrete surface to water and defrosting chemicals after 28 days | STN 73 1326 [51] |
| Shrinkage after 3 months curing in dry air | STN 73 1320 [52] |
| Creep after 3 months curing in dry air | STN 73 1320 [52] |
| Thermal conductivity coefficient | STN EN 12667 [53] |

4.7. Determination of k-Value of RBW Powder

The k-value calculation of the RBW powder is based on the determination of 28 day compressive strengths of the REF-2 and EXP-2 concrete. The 30 various concrete mixtures differ with two dosages of the cement (260 kg/m³ and 360 kg/m³), two specific surface
areas of RBW powder (300 m²/kg and 500 m²/kg) at 10 wt % cement replacement by the RBW powder and 5 water to cement ratios (0.40, 0.45, 0.50, 0.55, and 0.60), were prepared. The consistency of fresh concrete mixtures was recognized by the slump-test method. The 28 days cube compressive strengths were determined, and the respective k-values were calculated from the regression of the observed dependencies according to the TNI CEN/TR 16639. The k-value determines the strength equivalence between REF-2 and EXP-2 concrete. The STN EN 206 + A1 prescribes the determined k-value for each pozzolan in conjunction with the used cement. Until a pozzolan has not determined the k-value, it must not be applied in any construction concrete.

4.8. Resistance to Carbonation

Verification of the correctness of the RBW powder k-value was performed for use in XC2. Resistance to carbonation was assessed on the mortars by the accelerated carbonation test (ACT) in the carbonation chamber according to the TSÚS Methodology [30,31]. The resistance of EXP-2 mortar containing RBW powder having a specific surface area of 300 m²/kg and a k-value of 0.5 was compared with that of the REF-2 mortar. The k-value found for RBW powder at the previous concrete tests was used in determining the material composition of the EXP-2 mortar (Table 4). This step was taken to apply the ACT results to the concrete. The TNI CEN/TR 16639 enables performing the accelerated tests to determine the durability of smaller samples when the mortars of related components are used for this purpose. The mortars (40 × 40 × 160) mm were conditioned to constant weight before transferring to the climate chamber. The ACT was performed for 28 days in air saturated with 20% vol. CO₂ at (20 ± 1) °C and 50% relative humidity (RH). The second half of mortar specimens were treated only in reference (20 ± 1) °C/50% RH air.

Table 4. Mortar mixture compositions.

| Mortar Designation | Constituent (g) | Water to Cement Ratio w/(c + k × a) |
|--------------------|----------------|-------------------------------------|
| REF-2              | CEM II/B-S 42.5 N (c) 0.00 Water (w) 270 Standard Sand 1350 | 0.6 |
| EXP-2              | 426.32 RBW Powder (a) 47.37 | 270 1350 0.6 |

5. Results and Discussion

5.1. Suitability of RBW Powder as a Pozzolanic Type II Addition

Pozzolanic reactivity of RBW powder with other pozzolans is compared in Figure 1. Both RBW powder modifications show pozzolanic reactivity similar to broadly used fly ash and ground blast-furnace slag. RBW powders are classified as medium active pozzolans and, therefore, suitable for use in concrete.

5.2. Performance Properties of Aggregate

The chemical criteria for the suitability of (NA + RBW 0/4 mm) aggregates for use in concrete are specified for chloride ion content, sulfur compounds, and other constituents that alter the rate of setting and hardening concrete and affect the volume stability. The maximum water-soluble and acid-soluble chloride ion content must be 0.1 wt % Acid-soluble sulfate content is given by the value ≤0.2%. Total sulfur may not exceed 1 wt %. The influence of water-soluble materials occurring in (NA + RBW) blend aggregates on the initial setting time of cement paste is less than ≤40 min. The proportion of organic material may be such that they do not increase the setting time of mortar test specimens by more than 120 min and decrease the compressive strength of mortar test specimens by more than 20% at 28 days.

Tables 5–12 compare the test results of three tested aggregates: RBW 0/4 mm, NA 0–32 mm, and (NA + RBW 0/4 mm) blend, which are important for assessing the suitability of use as aggregates in concrete. Figure 2 compares the mineral composition of RBW
0/4 mm and (NA 0/32 mm + RBW 0/4 mm) blend, while the difference in their phase composition is illustrated in Figures 3 and 4.

![Comparison of pozzolanic reactivities of RBW 300 m²/kg and RBW 500 m²/kg with other pozzolans (MK—metakaolin, CD—clayey diatomite, CCD—calcined clayey diatomite, Z—zeolite, FA—fly ash, GBFS—granulated blast-furnace slag, CFS—cupola foundry slag).](image)

Figure 1. Comparison of pozzolanic reactivities of RBW 300 m²/kg and RBW 500 m²/kg with other pozzolans (MK—metakaolin, CD—clayey diatomite, CCD—calcined clayey diatomite, Z—zeolite, FA—fly ash, GBFS—granulated blast-furnace slag, CFS—cupola foundry slag).

Table 5. Chemical properties of aggregates.

| Property                                | Test Result |
|-----------------------------------------|-------------|
|                                         | Fine RBW    | NA           | (NA + RBW) Blend |
| Water-soluble chloride ion content       | 0.005 wt %  | 0.000 wt %  | 0.000 wt %      |
| Acid-soluble chloride ion content        | 0.019 wt %  | 0.0000 wt % | 0.001 wt %      |
| Acid-soluble sulfate                     | 0.50 wt %   | 0.02 wt %   | 0.11 wt %       |
| Total sulfur                             | 0.21 wt %   | 0.02 wt %   | 0.05 wt %       |
| Presence of organic material (humus)     | without any | without any | without any     |
|                                         | organic material | organic material | organic material |
| Constituents that alter the rate of      | Tests not performed | by 15 min     | by 15 min       |
| setting and hardening of concrete:       |             |            |                |
| Setting time—increase                    |             | by 15 min  |                |
| Compressive strength—decrease           |             | by 6%      | none           |

Chemical properties seem to be most unfavorable for fine RBW. Any negative impact of the (NA 0/32 mm + RBW 0/4 mm) blend on the properties of concrete is eliminated.

The fines content of the (NA + RBW) aggregate is considered non-harmful because the standard describes \( \leq 3 \) wt % of fines. The addition of RBW to NA to create (NA + RBW blend) only slightly increases the fines content. However, fine RBW alone is characterized by a high proportion of fine grains. This fraction does not meet the condition of the maximum limit of fines \( \leq 3 \). The results show that replacing a part of the NA 0/4 mm fraction with the 0/4 mm RBW fraction does not cause any obvious change in the grain composition of the resulting (NA + RBW) blend.
Table 6. Geometrical characteristics of aggregates.

| Grading at Dry Sieving-Percentage Passing (mm) | Test Result |
|-----------------------------------------------|-------------|
|                                               | Fine RBW    | NA           | (NA + RBW) Blend |
| 31.5 - 100 wt %                               | -           | 100 wt %     | 100 wt %         |
| 22.4 - 88 wt %                                | -           | 88 wt %      | 87 wt %          |
| 16 - 75 wt %                                  | -           | 75 wt %      | 74 wt %          |
| 11.2 - 66 wt %                                | -           | 66 wt %      | 62 wt %          |
| 8 - 58 wt %                                   | -           | 58 wt %      | 53 wt %          |
| 5.6 - 51 wt %                                 | -           | 51 wt %      | 45 wt %          |
| 4 - 46 wt %                                   | 99 wt %     | 46 wt %      | 41 wt %          |
| 2 - 33 wt %                                   | 86 wt %     | 33 wt %      | 32 wt %          |
| 1 - 23 wt %                                   | 58 wt %     | 23 wt %      | 22 wt %          |
| 0.5 - 15 wt %                                 | 36 wt %     | 15 wt %      | 14 wt %          |
| 0.25 - 6 wt %                                 | 18 wt %     | 6 wt %       | 6 wt %           |
| 0.125 - 2 wt %                                | 7 wt %      | 1 wt %       | 2 wt %           |
| 0.063 - 0 wt %                                | 0 wt %      | 0 wt %       | 0 wt %           |
| The fines content (≤0.063 mm)                 | 17.7 wt %   | 1.6 wt %     | 3.0 wt %         |

Table 7. Physical properties of aggregates.

| Property                                      | Test Result |
|-----------------------------------------------|-------------|
|                                               | RBW         | NA           | (NA + RBW) Blend |
| Loose density of loose aggregates             | 1.20 kg·m⁻³ | 1.86 kg·m⁻³ | 1.81 kg·m⁻³     |
| Loose density shaken aggregates               | 1.50 kg·m⁻³ | 2.08 kg·m⁻³ | 2.01 kg·m⁻³     |
| Apparent bulk density                         | 2.52 Mg·m⁻³ | 2.72 Mg·m⁻³ | 2.70 Mg·m⁻³     |
| Bulk density of oven-dried aggregates         | 2.12 Mg·m⁻³ | 2.63 Mg·m⁻³ | 2.62 Mg·m⁻³     |
| bulk density of water-saturated and surface-dried aggregates | 2.27 Mg·m⁻³ | 2.66 Mg·m⁻³ | 2.65 Mg·m⁻³     |
| Water absorption (24 h immersion in water)    | 7.6 wt %    | 1.0 wt %     | 1.2 wt %         |

Table 8. Volume stability of aggregates.

| Property                                      | Test Result |
|-----------------------------------------------|-------------|
|                                               | RBW         | NA           | (NA + RBW) Blend |
| Alkali–silica reactivity—ASR (STN 72 1179)    | R (alkalinity loss) = 40.04 * R (alkalinity loss) = 79.23 * |
|                                               | S (SiO₂ content) = 18.37 * S (SiO₂ content) = 17.60 * |
| Chemical test (mmol·L⁻¹)                       | Not performed | R (alkalinity loss) = 40.04 * S (SiO₂ content) = 18.37 * | R (alkalinity loss) = 79.23 * S (SiO₂ content) = 17.60 * |
|                                               | 0.018 (3 months) 0.021 (6 months) | 0.016 (3 months) 0.018 (6 months) |
| Dilatometry test (%)                           | Not performed | 0.018 (3 months) 0.016 (3 months) |
| XRD and TG-DTA technique as supplementary tests| Not performed | Undetected presence of minerals potentially evocative ASR Undetected presence of minerals potentially evocative ASR |
| Length changes-STN 73 1320                     | Not performed | 0.032% (6 months) 0.019% (6 months) |

Note: * if R > 70 than S < R and if R < 70 than S < 35 + R/2.
Table 9. Content of natural radionuclides in aggregates.

| Property                          | Test Results                      |
|----------------------------------|-----------------------------------|
|                                  | RBW | NA  | (NA + RBW) Blend |
| Activity concentration (Bq·kg⁻¹) |      |     |                  |
| 40 K                             | 615.1 | 338.7 | 322.9          |
| 226 Ra                           | 47.6  | 19.8  | 25.4            |
| 232 Th                           | 14.1  | 11.8  | 14.1            |
| Mass activity index (-)          | 0.58  | 0.23  | 0.26            |

Table 10. Comparison of the results in terms of landfilling of (NA + RBW) blend aggregate.

| Indicator                          | Limit Values (mg·kg⁻¹ Dry Solids) | Measured Values (mg·kg⁻¹ Dry Solids) | Rating |
|------------------------------------|-----------------------------------|--------------------------------------|--------|
| Sum of hydrocarbons (C10–C40)     | 50,000                            | 25.00                                | suits  |
| Total cyanides (CN⁻)              | 10,000                            | 0.13                                 | suits  |
| Mercury (Hg)                      | 3000                              | 0.02                                 | suits  |
| Arsenic (As) *                    | 5000                              | 9.00                                 | suits  |
| Lead (Pb) *                       | 10,000                            | 37.00                                | suits  |
| Cadmium (Cd)                      | 5000                              | <2.00                                | suits  |
| Nickel (Ni) *                     | 5000                              | 23.00                                | suits  |
| Total solutes (TS)                | 300,000                           | 2 160                                | suits  |

Note: * optional indicator, its choice depends on the nature of the received waste. Limit concentrations of monitored indicators have not been exceeded. Material can be landfilled.

Table 11. Composition of the water extract of (NA + RBW) blend and comparison with limit values for individual classes of the leachability of a waste.

| Indicator                          | Limit Values (mg·L⁻¹/Except of pH/) | Measured Values (mg·L⁻¹/Except of pH/) | Rating |
|------------------------------------|--------------------------------------|----------------------------------------|--------|
|                                   | Landfill Classes                     |                                        |        |
|                                   | LIW   | LNHW | LHW   |          |        |
| pH                                 | I.    | II.  | III.  |          |        |
| Aluminum (Al) *                   | 2     | 50   | -     | 1.00     | IW     |
| Arsenic (As)                      | 0.05  | 0.2  | 2.5   | 0.001    | IW     |
| Barium (Ba)                       | 2     | 10   | 30    | 0.018    | IW     |
| Cadmium (Cd)                      | 0.004 | 0.1  | 0.5   | <0.0003  | IW     |
| Cobalt (Co) *                     | 0.1   | 1    | 5     | <0.002   | IW     |
| Chromium (Cr)                     | 0.05  | 1    | 7     | <0.008   | IW     |
| Copper (Cu)                       | 0.2   | 5    | 10    | 0.003    | IW     |
| Mercury (Hg)                      | 0.001 | 0.02 | 0.2   | 0.0001   | IW     |
| Molybdenum (Mo)                   | 0.05  | 1    | 3     | <0.004   | IW     |
| Nickel (Ni)                       | 0.04  | 1    | 4     | <0.002   | IW     |
| Lead (Pb)                         | 0.05  | 1    | 5     | <0.005   | IW     |
| Indicator                  | Landfill Classes | Measured Values (mg L⁻¹/Except of pH) | Rating |
|---------------------------|------------------|---------------------------------------|--------|
|                           | LIW | LNHW | LHW |                           |        |
|                           |     |      |     |                           |        |
| **Leachability Class**    |     |      |     |                           |        |
|                           | I.  | II.  | III.|                           |        |
| Antimony (Sb)             | 0.006 | 0.07 | 0.5 | <0.001                    | IW     |
| Selenium (Se)             | 0.01 | 0.05 | 0.7 | <0.001                    | IW     |
| Tin (Sn) *                | 0.2  | 5    | 20  | <0.03                     | IW     |
| Vanadium (V) *            | 0.05 | 2    | 10  | <0.003                    | IW     |
| Zinc (Zn)                 | 0.4  | 5    | 20  | 0.004                     | IW     |
| Chlorides (Cl⁻)           | 80   | 1500 | 2500| 2.31                      | IW     |
| Florides (F⁻)             | 1    | 15   | 50  | <0.1                      | IW     |
| Sulfates (SO₄²⁻)          | 100  | 2000 | 5000| 50.2                      | IW     |
| Phenolic index (PNI)      | 0.1  | 50   | 100 | <0.01                     | IW     |
| Degradable organic carbon (DOC) | 50  | 80   | 100 | 1.1                       | IW     |
| Ecotoxicity (mL L⁻¹)      | Negative | 10 | -   | Negative                  | IW     |
| Total solutes (TS)        | 400  | 6000 | 10,000 | 216                     | IW     |
| Easily releasable cyanides | 0.02 | 1    | 2   | 0.013                     | IW     |

Note: * optional indicator, its choice depends on the nature of the received waste. LIW—landfill for inert waste, LNHW—landfill for non-hazardous waste, LHW—landfill for hazardous waste, IW—met limits for landfill for inert waste.

Table 12. Comparison of the analyses of the native sample with the limit values of indicators for individual classes of the landfills.

| Indicator                  | Landfill Classes | Measured Values (mg kg⁻¹ Dry Solids) | Rating |
|---------------------------|------------------|--------------------------------------|--------|
|                           | LIW | LNHW | LHW |                           |        |
|                           |     |      |     |                           |        |
| **Limit Values (mg kg⁻¹ Dry Solids)** |     |      |     |                           |        |
|                           |     |      |     |                           |        |
| TOC (total organic carbon) (wt %) | 3  | 5    | 6   | <0.05                     | IW     |
| C10–C40                   | 500 | 1000 | 50,000 | <125                   | IW     |
| Arsenic (As) *            | 200 | -    | 5000 | <29                      | IW     |
| Cadmium (Cd)              | 4   | -    | 5000 | <2                       | IW     |
| Mercury (Hg)              | 2   | -    | 3000 | 0.02                     | IW     |
| Nickel (Ni) *             | 500 | -    | 5000 | 23                       | IW     |
| Lead (Pb) *               | 500 | -    | 10,000 | 37                     | IW     |

Note: * optional indicator, its choice depends on the nature of the received waste. LIW—landfill for inert waste; LNHW—landfill for non-hazardous waste; LHW—landfill for hazardous waste; IW—meet limits for landfill for inert waste.

The (NA + RBW) blend meets the requirement of STN 72 1179 for aggregates that do not contain reactive forms of quartz. Both types of aggregates record as content-dominated minerals quartz Q (quartz)–SiO₂, limestone calcite Cc (CaCO₃), and dolomite D (CaCO₃ × MgCO₃) modification. NA contains more dolomite and less calcite. Both aggregates are characterized by approximately the same minority of albite AL–(Na, Ca) Al (Si, Al)₂O₈, which belongs to the group of feldspars, osmutilite OS–K–Na–Ca–Mg–Fe–Al–Si–O–H₂O characterized as a solid inorganic solution with a crystalline character and
muscovite $\text{Mu-H}_2\text{KAl}_3\text{(SiO}_4\text{)}_3$ classified as a clay mineral. The presence of minerals causing an alkali–silica reaction with the cement is not proved.

![XRD patterns of two different aggregate types](image)

**Figure 2.** XRD patterns of two different aggregate types.

![TG-DTA plots of the natural aggregate](image)

**Figure 3.** TG-DTA plots of the natural aggregate.

![TG-DTA plots of the blend of natural aggregate with recycled brick waste](image)

**Figure 4.** TG-DTA plots of the blend of natural aggregate with recycled brick waste.
Both aggregate types show a decisive loss on ignition by releasing CO\textsubscript{2} bound in calcite and dolomite between 700 \textdegree C and 850 \textdegree C. This is confirmed by DTA plots by an endothermic double deflection, with a smaller endotherm in the first left indicating the thermal decomposition of dolomite and a second larger dissociation of calcite. The material similarity of both aggregate types is recorded by XRD and TG-DTA methods. The addition of recycled brick waste on a change in the mineral and phase composition compared to pure natural aggregates is negligible. A fine depression, indicating a weak endotherm with a maximum at about 300 \textdegree C, is attributed to the loss of bound water from the marginally present osumilite. Highly similar material compositions and dominant representations of quartz, dolomite, and calcite in the studied aggregates are confirmed by both techniques. None of the aggregates contains minerals potentially evoking the alkali–silica reaction of the aggregate with the cement or water-active natural clays, which harm the concrete performance. The influence of marginally present muscovite is negligible. One would state that industrially processed clays after calcination eliminate this dangerous disadvantage for concrete volume stability.

The basic properties of aggregates concerning the protection of human health and the outer environment, which are an integral part of the certification of aggregates intended for use in concrete, are presented in Tables 10–13.

**Table 13. The properties of CEM II/B-S 42.5 N according to STN EN 197-1.**

| Property Tested                  | Criterion According to EN 197-1 | Measured Value | Test Evaluation |
|----------------------------------|----------------------------------|----------------|-----------------|
| Content of sodium oxide          | Without criterion                | 0.24 wt %      |                 |
| Content of potassium oxide       | Without criterion                | 0.91 wt %      |                 |
| Equivalent of sodium oxide       | Min. 0.8 wt %                    | 0.84 wt %      | Meets           |
| 2 d compressive strength         | \(\geq10.0\) MPa                | 19.0 Pa        | Meets           |
| 7 d compressive strength         | Without criterion                | 34.5 MPa       |                 |
| 28 d compressive strength        | \(\geq42.5\) MPa and \(\leq62.5\) MPa | 50.1 MPa      | Meets           |
| 2 d flexural strength            | Without criterion                | 4.3 MPa        |                 |
| 7 d flexural strength            | Without criterion                | 6.6 MPa        |                 |
| 28 d flexural strength           | Without criterion                | 8.3 MPa        |                 |
| Initial setting                  | \(\geq60\) min                  | 235 min        | Meets           |
| Final setting                    | Without criterion                | 275 min        |                 |
| Soundness (expansion)           | \(\leq10\) mm                   | 0.5 mm         | Meets           |
| Specific gravity                 | Without criterion                | 2.940 kg/m\textsuperscript{3} |           |
| Specific surface area            | Without criterion                | 492.6 m\textsuperscript{2}/kg |           |

The values of the monitored properties are the most unfavorable for RBW 0/4 mm, but they all meet the legislative conditions in Slovakia for building materials intended for the constructions with living spaces (mass activity index must be <1). The addition of RBW 0/4 mm to NA 0/32 mm as a partial replacement for the natural 0/4 mm fraction confirms the applicability (NA + RBW) blended aggregate in concrete from the viewpoint of the danger caused by the radioactive radiation.

The measured values in the water extract are suitable for leachability class I in all monitored parameters.

The waste can be placed in a landfill for waste that is not dangerous.

The test results of the (NA 0/32 mm + RBW 0/4 mm) blend declare:

(a) the values of bulk density of loose aggregate, bulk density, and absorbency correspond to the values of natural mined aggregate (gravel);

(b) no organic substances are detected—the test for the presence of humus was negative,
(c) the content of water-soluble chloride ions in natural aggregates is considered not to be hazardous if its value is below 0.01% by mass—water-soluble chloride ions were not detected in the (NA + RBW) aggregate;

(d) the aggregate contains acid-soluble sulfates 0.11% by weight, thus meeting the requirement for the strictest category (≤0.2% by weight)—a slightly increased value compared to the pure NA was caused by the presence of recycled brick waste;

(e) the total sulfur does not exceed the permitted value of 1 wt %;

(f) the presence of reactive forms of aggregates, which could cause the concrete to expand, is not found—6 month dilatometric test unambiguously confirms the (NA + RBW) aggregate as non-susceptible for alkali–silicate reaction;

(g) the aggregate meets the requirements of the said decree for building materials intended for the construction of buildings with residential areas;

(h) the water extract of the aggregate meets the requirements of the valid legislation designation as inert waste, and its composition does not harm the environment or toxic effects on biotic systems;

(i) the aggregate does not contain substances that could negatively affect the volume stability of the made concrete.

The overall evaluation of (NA 0/32 mm + RBW 0/4 mm blend) aggregate is as follows: the tested aggregate meets all requirements of STN EN 12620 + A1 as well as requirements for radionuclide content, mass activity index, and on the properties as inert waste according to the values of selected indicators in the native state, in the water extract of waste and ecotoxicity. All values of monitored indicators are suitable for inert waste. The set of tests confirms the mechanical, geometrical, chemical, and ecotoxicological suitability of the (NA 0/32 mm, an RBW 0/4 mm blend) aggregate for use in concrete production.

5.3. Verification of TRITECH Eco-Designed Ready-Mixed Concrete

Basic properties of the used Portland-blast furnace slag cement, superplasticizer, and the utility properties of fresh and hardened concrete for TRITECH ecotechnology are listed in Tables 13–18.

Table 14. The properties of CEM II/B-S 42.5 N according to STN 72 1179.

| Property Tested       | Criterion According to STN 72 1179 | Measured Value | Test Evaluation |
|-----------------------|------------------------------------|----------------|----------------|
| Sodium oxide content  | Without criterion                   | 0.24 wt %      | -              |
| Potassium chloride content | Without criterion                   | 0.91 wt %      | -              |
| Sodium oxide equivalent | Minimum 0.8 wt %                     | 0.84 wt %      | Suits          |

Cement CEM II/B-S 42.5 N fulfills all the property requirements according to STN EN 197-1 and STN 72 1179. Superplasticizers SIKA 4025 and SIKA 4035 meet all the property requirements according to STN EN 934-2 + A1. All materials are, therefore, suitable for use in concrete production.

Both concrete (REF-1 and EXP-1) are characterized by fully comparable strength parameters at the age of 28 and 90 days. The chosen replacement does not deteriorate in any way, the rheological properties of fresh concrete, but also the strength. This finding is a realistic assumption for a comparable long-term service life of both concrete types. The obtained results prove the applicability of TRITECH Eco-designed ready-mixed concrete as an equivalent qualitative substitute for REF-1 concrete.
Table 15. The properties of superplasticizer SIKA 4025 according to STN EN 934-2 + A1.

| Property Tested                  | Criterion According to EN 934-2 + A1 | Measured Value | Test Evaluation |
|----------------------------------|--------------------------------------|----------------|-----------------|
| Sodium oxide content             | Without criterion                    | 0.20 wt %      | -               |
| Potassium chloride content       | Without criterion                    | 0.01 wt %      | -               |
| Sodium oxide equivalent          | ≤1.0 wt %                            | 0.21 wt %      | Suits           |
| Content of chlorides             | ≤0.10 wt %                           | 0.0005 wt %    | Suits           |

Table 16. The properties of superplasticizer SIKA 4035 according to STN EN 934-2 + A1.

| Property Tested                  | Criterion According to STN EN 934-2 + A1 | Measured Value | Test Evaluation |
|----------------------------------|--------------------------------------|----------------|-----------------|
| Sodium oxide content             | Without criterion                    | 0.22 wt %      | -               |
| Potassium chloride content       | Without criterion                    | 0.01 wt %      | -               |
| Sodium oxide equivalent          | ≤1.0 wt %                            | 0.23 wt %      | Suits           |
| Content of chlorides             | ≤0.10 wt %                           | 0.0009 wt %    | Suits           |

Table 17. Rheological properties of fresh concrete.

| Concrete Designation | Consistency by Flow-Table Test (mm) | Volume Density (kg/m³) | Air Content (vol %) |
|----------------------|-------------------------------------|------------------------|----------------------|
|                      | after Mixing                        | after 30 min Stay      |                      |
| REF-1                | 570                                 | 430                    | 2430                 | 1.5                  |
| EXP-1                | 560                                 | 480                    | 2380                 | 2.6                  |

Table 18. Main utility properties of concrete after 28- and 90 days curing in water.

| Concrete Designation and Age in Days | Volume Density (kg/m³) | Strength (MPa) | Elasticity Modulus (GPa) | Suction Capacity (%) | Resistance to Water Penetration under Pressure (mm) |
|--------------------------------------|------------------------|----------------|--------------------------|----------------------|---------------------------------------------------|
|                                      |                        | Compressive    | Flexural                 | Dynamic              | Young’s (Static)                                 |                                                  |
| REF-1-28                             | 2440                   | 34.9           | 5.8                      | 58.5                 | 36.7                                             | 4.03                                             | 35                                               |
| REF-1-90                             | 2440                   | 43.5           | 6.6                      | 60.1                 | 39.4                                             | 4.09                                             | -                                                |
| EXP-1-28                             | 2380                   | 36.6           | 5.0                      | 57.4                 | 33.0                                             | 4.51                                             | 33                                               |
| EXP-1-90                             | 2410                   | 43.6           | 6.3                      | 58.2                 | 38.1                                             | 4.48                                             | -                                                |

5.4. Determination of k-Values for RBW Powder

Tables 19 and 20 reveal 28 days compressive strengths of 30 different concretes. K-values were calculated from the regression of the observed dependencies based on the same strength conditions [27].

The estimated k-values for the CEM II/B-S 42.5 (N and R) contents are specified in Tables 21 and 22. K-values refer only to using CEM II/B-S 42.5 in concrete by the TNI CEN/TR 16,639. Another cement requires separate testing. The universal valid k-value of industrially made type II RBW addition TERRAMENT for use in concrete is k = 0.5. This k-value is applicable in the whole range of water to cement ratios, except that of 0.65 and higher, the content of the cement CEM II/B-S 42.5 260 kg/m³ and more, and a limit fineness of RBW powder between 300 m²/kg and 500 m²/kg. The RBW powder, as a pozzolanic type II addition, records higher k-values for individual water to cement ratios below 0.6, even up to that of 0.8. TERRAMENT meets the condition of using concrete with the specified k-value of type II addition prescribed in STN EN 206 + A1 and, therefore, can be applied industrially in the construction concrete.
Table 19. Compressive strength of concretes with cement/binder content of 260 kg/m³.

| Water–Binder Ratio w/(Cement + Addition) | Compressive Strength (MPa) |
|----------------------------------------|-----------------------------|
|                                         | REF-1 (Cement 260 kg/m³)   | EXP-1/1 (10% RBW 300 m²/kg) | EXP-1/2 (10% RBW 500 m²/kg) |
| 0.45                                   | 44.3                        | 43.5                         | 43.2                         |
| 0.50                                   | 40.6                        | 40.2                         | 41.0                         |
| 0.55                                   | 40.8                        | 38.8                         | 40.1                         |
| 0.60                                   | 37.9                        | 36.8                         | 34.6                         |
| 0.65                                   | 34.0                        | 32.1                         | 33.0                         |

Table 20. Compressive strength of concretes with cement/binder content of 360 kg/m³.

| Water–Binder Ratio w/(Cement + Addition) | Compressive Strength (MPa) |
|----------------------------------------|-----------------------------|
|                                         | REF-2 (Cement 360 kg/m³)   | EXP-2/1 (10% RBW 300 m²/kg) | EXP-2/2 (10% RBW 500 m²/kg) |
| 0.45                                   | 44.6                        | 43.0                         | 43.0                         |
| 0.50                                   | 38.7                        | 38.8                         | 39.4                         |
| 0.55                                   | 36.6                        | 34.3                         | 35.6                         |
| 0.60                                   | 33.4                        | 31.8                         | 30.0                         |
| 0.65                                   | 30.4                        | 27.1                         | 27.9                         |

Table 21. K-values of RBW powder for cement content 260–360 kg/m³ and 10 wt % cement replacement by RBW in concrete.

| Water–Binder Ratio w/(Cement + Addition) | k-Value |
|----------------------------------------|---------|
| CEM II/B-S 260–360 kg/m³ (Replacement by 10% RBW 300 m²/kg) | CEM II/B-S 260–360 kg/m³ (Replacement by 10% RBW 500 m²/kg) |
| 0.45                                   | 0.7     | 0.8                          |
| 0.50                                   | 0.6     | 0.7                          |
| 0.55                                   | 0.5     | 0.6                          |
| 0.60                                   | 0.5     | 0.5                          |
| 0.65                                   | 0.4     | 0.4                          |

5.5. Verification of the Durability Aspect—Resistance to Carbonation

To verify the resistance of the RBW powder of 300 m²/kg fineness (TERRAMENT) against aggressive CO₂, the cement mortars (REF-2 and EXP-2) with the already calculated value k = 0.5 were used for testing (see Table 4). Figures 5–8 show decisive REF-2 and EXP-2 mortar properties. The degree of carbonation was determined by the accelerated carbonation test (ACT) based on the TSÚS Methodology [30,31] from the chemical tests performed. Quantitative evaluation of the parameters determining the extent of carbonation in mortars is listed in Table 23. The TSÚS method of evaluation includes six individual change criterion ∆k based on the relevant standards for the design of concrete: STN EN 206 +A1, STN EN 1992-1-1 Eurocode 2 [54] and own diagnostic practice in the area of structural concrete [55,56].
Table 22. K-values of RBW powder for cement content 360 kg/m$^3$ and more and 10 wt % cement replacement by RBW in concrete.

| Water–Binder Ratio | CEM II/B-S 360 and More kg/m$^3$ (Replacement by 10% RBW 300 m$^2$/kg) | CEM II/B-S 360 and More kg/m$^3$ (Replacement by 10% RBW 500 m$^2$/kg) |
|--------------------|------------------------------------------------------------------------|---------------------------------------------------------------------|
| 0.45               | 0.7                                                                    | 0.8                                                                 |
| 0.50               | 0.6                                                                    | 0.7                                                                 |
| 0.55               | 0.5                                                                    | 0.6                                                                 |
| 0.60               | 0.5                                                                    | 0.5                                                                 |
| 0.65               | 0.4                                                                    | 0.4                                                                 |

Figure 5. Weight changes of the mortars at the ACT—samples kept in air (A) at (20 ± 1) °C and 50% RH and at (20 ± 1) °C/50% RH (CO$_2$) with 20% vol. CO$_2$.

Figure 6. Length changes during the ACT—samples kept in the air (A) at (20 ± 1) °C and 50% RH and in the carbonation chamber (CO$_2$) at (20 ± 1) °C/50% RH and 20% vol. CO$_2$.
The study of changes in monitored REF-2 and EXP2 mortar properties focusing on the evaluation of carbonation resistance shows that EXP-2 mortar has the potential for resistance to aggressive CO\textsubscript{2} against the influence of the XC2 environment of STN EN 206 + A1.

6. Conclusions

Based on a series of the performed tests, the following conclusions are drawn:

(1) The powdered recycled brick waste (RBW) together with 0/4 mm fraction partially replacing a part of cement and natural aggregate in the specified concrete mixture composition are declared as materials suitable for the production of industrially made TRITECH Eco-designed ready-mixed concrete of C 25/30 strength class;

(2) The type II RBW powder, as industrially made addition TERRAMENT, for use in concrete is characterized by the pozzolanic reactivity fully comparable to the standardized fly ash;

(3) The universal valid k-value of TERRAMENT is $k = 0.5$; this k-value applies to the whole range of water to cement ratios, except that of 0.65 and higher, the cement content of CEM II/B-S 42.5 (N and R) from 260 kg/m\textsuperscript{3} and more at the 10% weight

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**Table 23.** Quantitative evaluation of parameters determining the extent of carbonation in mortars.

| Mortar        | Change of Mortar Property after ACT Opposite Reference Exposure | Degree of Carbonation (%) |
|---------------|-----------------------------------------------------------------|---------------------------|
|               | Weight (%) Length Changes (%) Dynamic Elasticity Modulus (%) | Compressive Flexural |
| REF-2-CO\textsubscript{2} | 2.1  -0.188 0.6 | -3.2  -30.6 | 27.6 |
| EXP-2-CO\textsubscript{2} | 2.2  -0.173 -6.8 | 1.8  -14.4 | 32.5 |
| Change of d   | 0.1  0.015 -7.4 | 5.0  16.2 | 4.9  |
| Criterion Δk *| <5  <0.05 <10 | <10  <10  <15 |
| Evaluation    | meets meets meets | meets meets meets |

* Criteria of TSUS for changes in Δk in the mortar properties after the ACT.
percentage replacement of the cement by TERRAMENT. The k-values based on the specifically determined water to cement ratios vary from 0.5 to 0.8. One must consider that STN EN 206 + A1 does not allow using type II additions in concrete without a specified k-value;

(4) Experimental cement mortar EXP-2 (with calculated k-value 0.5) made with CEM II/B-S 42.5 and TERRAMENT, and at the same water to cement ratio as concrete that is confirmed by the respective k-value 0.5, is resistant to the influence of aggressive CO₂ on the XC2 environment as specified by STN EN 206 + A1. This means that concrete with TERRAMENT is, in the same way, durable to carbonation in the XC2 environment;

(5) The issued SK-technical assessments [20,21] for TERRAMENT type II addition and TRITECH Eco-designed ready-mixed concrete means at the national level the documents with the legitimacy equal to the Slovak technical standard (STN);

(6) Research to date carried out globally, especially in China, but also ours, proves that the secondary recovered natural clays are becoming a strategic raw material in the production of eco-friendly concretes.

TRITECH presents a new ecotechnology that enables using industrially processed recycled brick waste in the construction sector. TRITECH was certified in TSÚS, Bratislava and subsequently defended at the Austrian Standard Institute, Vienna, for using recycled 0/4 mm aggregate and powder in concrete. TRITECH ecotechnology and type II addition TERRAMENT based on RBW are the results of industrial and research cooperation between Austria and Slovakia.

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