Development of restoration mortars and artificial stones for use in restoring cultural heritage sites made from volcanic tuffs

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Abstract
Many historically significant buildings and cultural heritage sites are made of volcanic tuffs. These sites are subject to a progressive weathering and are partly in ruinous conditions. Preparing a suitable stone replacement mortar for repair work or even whole replacement stones for these rocks is of great interest. During the quarrying of tuff rocks, more than 40% of the material is rejected and cannot be further used. Utilizing this material, the production of replacement materials with optimized properties for the restoration and repair of severely damaged natural stones represents a resource-saving measure for the preservation of these buildings. In addition to the effective use of the natural stone waste, these artificial materials, in contrast to the very heterogeneous tuffs, offer a constant quality and consistent properties. A more effective exploitation can lead to a more sustainable usage of this natural resource and minimize the interference to the environment. This study describes the development of stone replacement mortars and the creation of artificial replacement stones utilizing source material from Mexico and Armenia. The resulting replacement material shows similar properties, aesthetics, and weathering behavior like the original rock, while different properties could be optimized. Petrophysical properties as well as the weathering behavior of the volcanic tuff rock were analyzed along with the developed replacement mortar and artificial stone. As hydric and thermohydric expansion processes are important factors for the durability of the investigated rocks, replacement materials were developed and optimized which, except for the pore structure of the cement and concrete matrix, show a high correspondence to the natural stones in terms of macroscopic appearance and technical properties. The compatibility of the replacement material with the original rock was investigated. Moreover, based on the evaluation of the mechanical as well as the pore space, water transport and weathering properties, the replacement stones were evaluated as equally suitable construction material, while the replacement mortars vary in regard to their results. Accordingly, the replacement stones developed in this study can be considered as full-fledged rock substitutes for the Armenian tuffs, while the replacement mortars for the Mexican tuffs partly show a good suitability and could be partially optimized.

Keywords Development of a restoration stone mortar · Artificial replacement stones · Source rocks from Mexico and Armenia · Technical properties · Color adaptation

Introduction
The inventory of many historical and valuable buildings and cultural monuments constructed from tuff stones are strongly endangered (Pötzl et al. 2022; Siegesmund and Pötzl 2022). Ornamentations, decorative sculptural elements, gravestones, decorative support columns, building facades, and historical monuments are especially significant structures or objects built from tuffs. Some examples from Mexico and Armenia are shown in Fig. 1A–H. Their intricacy of design is heavily affected by damages resulting from weathering. Tuff stones are readily available, easily extracted with a wide range of processing capabilities, which is due to their low...
strength and density, but in strong contrast to this aspect they show a pronounced susceptibility against weathering leading to extreme back-weathering and material loss. The question arises here, what suitable conservation and restoration measures can be implemented to reduce the loss of material or to minimize it in the intermediate term (Siegesmund et al. 2005; Török et al. 2005; Haist et al. 2009; Mertens and Sabatzi 2020; Klein 2021).

For the modern-day conservation of historical monuments, the main goal is to try and preserve the original material as much as possible. When tuff stones are not available for restoration measures, be it localized repair work or complete natural stone replacement, the information determined from the mineralogical and rock mechanical investigations of volcanic tuffs, can help in giving us parameters by which stone replacement materials (e.g., mortars or artificial stones) can be matched to the available inventory. Stone replacement mortars or artificially optimized replacement stones should be developed and tested for conservation applications. In this case, it must be checked whether suitable restoration mortars are available or whether they need to be redeveloped. Rilem defined mortar as a material composed of one or more inorganic binders, aggregates, water and admixtures used in masonry to provide for bedding, jointing and bonding of masonry units (Groot et al. 2004; final report of RILEM TC 167-COM).

Requirement profiles for restoration mortars must be adapted especially with regard to mechanical properties, chemical–mineralogical compatibility, physical properties and the optical compatibility. Figure 2A–B depicts two examples of poorly used non-adapted restoration mortars, which in Fig. 2B lead to very adverse effects. During the accompanying tests for an alternative solidifying agent, it is also important to consider the possible reduction of the swelling behavior in the tuff material. The extent, to which a replacement stone for damaged sections will be applied, also needs to be examined. Generally, the requirements for a replacement stone are visual, structural (fine-, medium-
coarse-grain size) and mineralogical properties. In addition, the petrophysical properties need to be specified. The replacement stone to be chosen should have similar petrophysical properties such as porosity, pore-radii distribution and water uptake as well as transport characteristics and strength properties. Four examples of replacement stones are shown in Fig. 2A–D.

For the replacement of severely damaged areas on buildings, tuff stones are not always available. Stone replacement materials, such as joint and application mortars, backfill mortars, etc., or even the development of artificial stones as a possible replacement substitute with optimized technical properties and similar visual appearance must be developed and tested. Cement, added water, trass powder, color pigments, aggregates, etc. are the starting materials for this process.

Within the scope of the present work, different binder mixtures are used for the production of stone replacement materials. Optimization of the binder mixtures would undoubtedly also make it possible to achieve other approaches to mortar and substitute block development with, where appropriate, better and/or more compatible properties. Stone replacement mortars are developed for some model cases, targeting selected tuff varieties. These stone replacement mortars are limited in their application possibilities (e.g., surface area and thickness), especially with regard to the repaired surface and the thickness of the applied mass. Here, crack formations and especially cracks parallel to the surface do not always close by recrystallization. Therefore, the second step was to develop model stone replacement compounds suitable for the production of artificial stones. To produce an artificial stone as a suitable substitute material, the replacement substitute must have similar properties to the original stone in terms of optical properties, water absorption, Young’s modulus, strength and weathering behavior. For this purpose, the aggregate is crushed to grain

Fig. 2 Application of stone replacement mortars and the use of artificial replacement stones. A Repair mortar and replacement stones at the church of Nstra, Señora Del Carmen in San Luis Potosí, Mexico (yellow arrows, RS = replacement stone), B Catastrophic decay by the use of concrete for the restoration of rhyolitic tuff (Torók et al. 2005), C Part of the tower façade of the St. Georg’s Church in Nördlingen (Germany), where larger areas were restored by artificial replacement stones (some outlined by the yellow dashed line) for the used impact stone “Suevite” (Mertens and Sabatzki 2020), and D Lighter colored artificial replacement stones (arrows) for the Habichtswald tuff used for the Hercules Monument in Kassel, Germany (see Drazic M 2010)
sizes similar to those used in concrete. Cement, admixture water, pulverized cement, color pigments and aggregates, etc. are the starting materials for this process.

Such artificial stones are to be used when corresponding natural stones cannot be quarried and are, therefore, the only available substitute. This study examines whether an artificial stone can be produced from quarry waste, which can function as a fully adequate tuff substitute stone and has the required technical properties and optical characteristics for the installation work.

For the creation of stone restoration mortars and compatible artificial replacement stones for volcanic tuffs, it is necessary to determine the mineralogical composition, define the macroscopic and microscopic fabric, their geochemistry and classification. In this study tuffs from Mexico and Armenia were chosen as the source material for the development of stone restoration materials. The varieties San Miguel del Alto (SMA), Cantera Rosa (CR), Cantera Verde (CV) and Loseros (LOS) are the Mexican tuffs chosen for developing a stone replacement mortar (Fig. 1A–D). The Armenian tuffs comprise Artik Rosa (AR), Golden Armenia (GA), Gyumri Black (GB), and the Sissian (SI) basalt as the source rocks (Fig. 1E–H) used for developing artificial replacement stones. Table 1 summarizes the mineralogical composition and the petrographic features (see also Siegesmund et al. 2022a, b and Pötzl et al. 2018).

This study presents preliminary results for the development of stone replacement mortars for localized repair work and artificially produced replacement stones for frequently used tuff rocks. Several binder mixtures are compared with each other using Portland cement and CaO. To match the color of the original stone, systematic test series were performed. Mortar systems are particularly critical in terms of strengths, so there should be a low modulus of elasticity and/or compressive strengths to absorb stresses and thus prevent the problem of cracking. High evaporative conductivity after moisture penetration is also desired. Another critical parameter, especially in the case of tuff rocks, is the swelling behavior, and it is, therefore, necessary to check to what extent a possible reduction can be produced.

Preparation of restoration materials and testing methods applied

Adaptation and preparation of the restoration mortar

The four tuff rocks SMA, CR, CV, and LOS were crushed and sieved to a fraction ≤ 1 mm and utilized as a raw material for the stone replacement mortars (SRM). In the production of SRMs, the aggregate as an additive should have an optimal as possible grading curve and at the same time be adapted to the desired maximum grain size (Snethlage and Pfanner 2020).

From both, an aesthetic and a craftsmanship point of view, it should be noted that the matrix of a natural tuff stone usually has a much smaller grain or particle size than a mortar, since the latter consists of binder and aggregate. As a result, an aesthetically adapted restoration mortar usually has a much finer aggregate than a conventional plaster or masonry mortar. The grading curve of restoration mortars is, therefore, primarily determined by fine sands and can only be described as "poorly graded". However, a stone replacement mortar should never have a static task, but rather an aesthetic and rock-protecting one.

Grading curves were generated as an example on the four source rocks from Mexico (Fig. 3). While the grading curves of all tuff rocks are dominated by a fine fraction, the general distribution of CV, LOS, and CR is comparable, with a high proportion of aggregates between 0.5 and 0.25 mm. The grading curve of the SMA tuff on the other hand, is more balanced, with similar proportions of the different mesh sizes and the highest amount of aggregates smaller than 0.065 mm.

The SRMs in this study are based on a binder, crushed tuff rock and pigments in different quantities. Based on the work of Teipel et al. (2020), different mixtures were used as the binder material. All samples named with the abbreviation CaO contain a mixture of white Portland cement (CEM I 42,5 N, Dyckerhoff) and CaO (80% Calcium oxide, Otterbein) in the weight ratio 1:2.6. The CEM samples contain a mixture of Portland limestone cement (CEM II/A-LL 42.5, Dyckerhoff) and trass powder (Tubag) in a 12:1 weight ratio.

Color series were created in advance for each variety to achieve the most suitable SRM coloration. The color matching was selected with respect to the matrix coloration of the original rock. The coloring with natural oxide pigments was carried out stepwise as shown in Fig. 4. The pigment content was adjusted until the best possible color match to the original rock was achieved (Fig. 5). Color pigment content did not exceed 0.6 wt.%. The final mixtures for the SRMs utilizing Mexican tuffs are listed in Table 2.

The final mixture of all aggregates was used to create the SRM test samples. SRMs were prepared in cubic molds (65*65 mm), prisms (40*40*160 mm and 5*5*50 mm) and cylindrical molds with a diameter of 40 mm and a height of 40 mm. After 24 h the specimens were removed from the molds and the CaO samples were stored for 28 days at a temperature of 20 °C and 60% rh, according to the DIN EN 206-1 (2001) and DIN 1045-2 (2008). The CEM samples
| Sample             | Classification | Characteristics and composition | Mineralogy | Microscopic |
|--------------------|----------------|---------------------------------|------------|-------------|
| Armenia Tuffs      |                |                                 |            |             |
| Artik Rosa (AR)    | Vitric tuff    | Highly porous tuff which is pink to reddish in color. Contains various type of lapilli, mostly clasts of pumice (cm to dm in size). Clasts show red, brown and gray colors. Open pores visible in the pumice clasts. | Major components: plagioclase, cristobalite/tridymite (determined by XRD) and K-feldspar; trace components: muscovite/filitte, clinopyroxene and hematite. | Shows a porphyritic fabric with varying amounts of large feldspar crystals. Relict amphiboles and muscovites occur. Lithic clasts are intermediate in composition and embedded in a cryptocrystalline, glassy matrix. Considerable iron oxides cover the matrix and the clasts. Apatites and prismatic amphibole observed in larger pore spaces. Rare, fine-grained pyroxene occurs. |
| Golden Armenia (GA)| Crystal tuff   | Tuff shows a light brownish yellow to yellowish golden matrix. Wide range of volcanic lithic clasts occur showing reddish, white, light yellow, beige, light green, dark brown and black colors. Clasts are <1 mm to 1 cm, some elongated to angular | Major component: corrensite; minor components: quartz, K-feldspar, augite and muscovite/filitte; Trace components: plagioclase, opaques, and prismatic apatite (observed under the SEM). | In thin section, glass-rich matrix exhibiting high amounts of volcanic clasts and feldspar relics occur. K-feldspar quite weathered, often showing alteration to sericite along crystal edges. Trace plagioclase shows polysynthetic twinning. |
| Gyumri Black (GB) | Vitric tuff    | Abundant millimeter sized clasts showing white, black, reddish-brown colors embedded in a fine-grained black matrix. Glassy clasts occur and are elongated in shape; black pumice clasts attain sizes up to 10 mm and reddish-brown clasts show rounding. | Dominant components: volcanic glass and K-feldspar; major component: plagioclase; minor components: clinopyroxene and orthopyroxene; trace component: muscovite/filitte. | Preferred direction is discernible. Microstructure also shows chaotic areas. High proportions of glass and K-feldspar are visible. Glassy matrix shows intercalated feldspar phenocrysts. Volcanic lithiclasts make up around 10–15 percent in thin section. |
| Sissian (SI)       | –              | Matrix of this vesicular basalt is light gray; shows a porphyritic fabric; vesicles visible up to the millimeter range; inclusions of greenish olivine and dark gray clinopyroxene are visible. | Major components: K-feldspar and plagioclase; minor components: muscovite/filitte, clinopyroxene and olivine. | Rock shows a porphyritic and holocrystalline fabric where fine-grained plagioclase laths (needle-like) are embedded in the groundmass. Hypidiomorphic augite and fractured olivine phenocrysts are located in the plagioclase-rich groundmass. Opaque phases occur but are unidentified. Vesicles make up around 5 percent in thin section. |
| Sample             | Classification | Characteristics and composition                                                                 |
|--------------------|----------------|---------------------------------------------------------------------------------------------|
| Mexican Tuffs      |                |                                                                                              |
| Cantera Rosa (CR)  | Crystal tuff   | Reddish-brown tuff with dominantly altered white lithoclasts; minor gray clasts and red scoria; lenticular & angular black fragments; matrix is v.f.g |
|                    | Tuff           | Major components: quartz and smectite (swellable clay); K-feldspar, plagioclase, muscovite/illite and kaolinite are minor components |
|                    | Dacite         | Ash layers mostly opaque; hypocrystalline fabric; mm sized crystals are very broken; feldspars also broken as K-feldspar and plagioclase; large pore spaces due to weathered out clasts; matrix consists of v.f.g. crystals and altered crystals defined by dark brown extremely f.g. material (hematite); minor altered biotite?; devitrified clasts; dominant phase quartz |
| Cantera Verde (CV) | Crystal tuff   | Light to dark shades of green, massive rock; considerable lithoclasts                         |
|                    | Ash tuff       | Major components: cristobalite (determined by XRD), K-feldspar and heulandite; minor components: muscovite/illite, chlorite, mordenite and smectite (swellable clay); possible traces of kaolinite |
|                    | Dacite         | Ash-rich hypocrystalline fabric; shard structures visible in matrix; devitrification of glass; lithic fragments are basalt & opaques; crystals fractured; indications of flow |
| Loseros (LOS)      | Lithic tuff    | Very fine laminations; green reddish-brown or light gray in color; fine-grained, well-sorted volcanoclastic rock |
|                    | Ash tuff       | Major components: quartz and smectitic-mixed layer clay minerals; major components: calcite, K-feldspar and plagioclase; minor components: cristobalite/tridymite, glass and smectite (swellable clay); trace components: muscovite/illite, kaolinite |
|                    | Dacite         | Ash layers almost opaque; groundmass is v.f.g. crystallites; feldspars altered; relict shards; hypocrystalline to holohyaline fabric. Mostly lithic fragments of basalt/trachyte. Significant weathering & replacement by calcite + sericite + chloride + epidote |
| San Miguel del Alto (SMA) | Vitric tuff   | Dark rose colored tuff, fine-grained homogenous matrix; many elongated pumice clasts some > 1 cm in size; direction of flow also indicated, pumice clasts also weathered out; some mottling due to oxidation of Fe-rich lithic fragments |
|                    | Lapilli Tuff   | Major components: quartz, plagioclase and smectitic-mixed layer clays; minor components: K-feldspar and tridymite (determined by XRD) |
|                    | Rhyolite       | Rock shows a holohyaline fabric with only very coarse crystals of K-feldspar; groundmass is very fine-grained, which consists of anhedral quartz and feldspar embedded in a glass-rich matrix; relict devitrified glass shards are evident and indicated by very fine-grained crystals; opaques are also visible |
were completely immersed under water and stored for 7 days before these were also deposited at 20 °C and 60% rh. After 28 days of standardized drying conditions, all SRM samples were placed in a drying cabinet with a temperature of 40 °C until mass constancy.

**Fig. 3** Example of grading curves for the Mexican tuff varieties used for developing the stone replacement mortars

**Fig. 4** Color scheme of the different mortar formulas (CaO and CEM) for Cantera Rosa (CR) and San Miguel el alto (SMA). 0% is the initial state, without pigment added; the following images show the increasing pigment content of iron oxide red in weight percent

**Materials and mixing recipes for the artificial replacement stones**

For the development of the artificial replacement stone with optimized technical and optical properties different raw
Fig. 5 Visual comparison of the Mexican tuff rocks (left row) and the final mortar mixtures (CaO in the middle and CEM on the right)

Table 2 Mixing formula for 100 g of the respective replacement mortar

| Sample | Binder | Binder/Tuff/Powder/Ratio | Pigments (%) | Water (g) |
|--------|--------|--------------------------|--------------|-----------|
| CR     | CaO    | 1:3                      | 0.05 cobalt blue 0.2 brown 0.35 red | 38       |
| CEM    | 1:3    | 0.2 red                  |              | 32       |
| CV     | CaO    | 1:3                      | 0.4 umber green | 43       |
| CEM    | 1:3    | 0.1 umber green 0.25 white 0.05 yellow | 37       |
| LOS    | CaO    | 1:3                      | 0.3 cobalt blue 0.3 umber green | 33       |
| CEM    | 1:3    | 0.2 cobalt blue 0.4 umber green | 29       |
| SMA    | CaO    | 1:3                      | 0.2 cobalt blue 0.2 red | 38       |
| CEM    | 1:3    | 0.1 cobalt blue 0.3 red 0.2 white | 32       |
materials have been used. Cement, water, and aggregate crushed from the respective natural stone are the main constituents. In addition, trass powder, color pigments, superplasticizer, and air-entraining agents have been used.

The requirement for a frost-resistant aggregate can be fulfilled on the basis of the results of the freeze–thaw tests of the natural stones, as the mass of the weathering of the test cubes were below the limit value. For the best possible supporting structure of the replacement stone the void volume is minimized, the aggregate composition is to be determined according to the standard grading curves of DIN 1045–2 (2008). To determine the maximum particle size (Dmax), the size of the clasts and inclusions of the parent rock was analyzed. For the samples Golden Armenia, Gyumri Black, and Sissian these are in the millimeter range and clearly below the standard grading curve with the smallest Dmax of 8 mm.

According to DIN 1045–2 (2008), a grading curve A/B 8 in the favorable range (coarse to medium-grained, range 3) was chosen for all mixtures, as this aggregate composition is optimal for replacement stones with high freeze–thaw resistance, water penetration resistance and wear resistance, and provides a medium water and cement demand with a medium heat development (Schäffler et al. 2000). Based on the determination of the granulation number (k value), the water demand could be calculated and the water–cement ratio analyzed. Based on these data, the composition of the different mixtures was determined, and test specimens were prepared.

Considering the results of the first replacement stone test specimens, the mixtures were adjusted to optimize the optical appearance, if necessary, and to ensure frost resistance. Therefore, the pigment contents were partly modified, and air-entraining agents were added together with the admixture water during the production of the fresh samples ARB2, SI2, SI3, GY2, and GA2. Furthermore, an attempt has been made to increase the proportion of superplasticizer in order, under certain circumstances, to reduce the amount of water required for the pretreatment of the aggregates. In Table 3 the formula for the Artik Tuff is given as an example.

### Sample preparation of the artificial replacement stones

Cube molds made of silicone with an edge length of 100 mm as well as cuboid molds made of screen printing plates were used for the production of the test specimens for the flexural strength. The creation of color series for the determination of the optimum cement paste coloration and first test specimens was carried out with cube-shaped plywood molds with edge lengths of 40 mm and 65 mm, respectively.

Before filling the molds, they were coated on their inner surfaces with a thin layer of non-reactive release agent so that the concrete does not adhere. Subsequently, the molds were filled in three layers, each of which was compressed by hand compaction (DIN EN 12390-2 (2019)). Thus, air pockets, but no artificial air voids, escape, after the compaction of each layer, the outer walls of the molds were tapped until no more air bubbles rose to the surface. Accordingly, the test specimens were stored for 24 h at 20 °C after production, protected against drying and then demolded (DIN EN 12390-2 (2019)/A20, 2015). The concrete cubes were then placed in a water bath for 6 days. Afterwards the test specimens were stored in a climate chamber at 20 °C and 65% relative humidity.

### Testing methods

One of the most important aspects of stone replacement mortars or artificial stones is their compatibility with the original rock, to avoid or prevent further stone decay. Therefore, different investigations of the tuff source rocks, the stone replacement mortars and artificial stone material have been performed to determine their suitability as a substitute restoration material.

Cubic samples (65 mm edge length) were used to perform hydrostatic weighing to determine the porosity, bulk and particle density, according to DIN 772–4 (1998) and the capillary water absorption coefficient (w value) according to DIN EN ISO 15148 (2018). The pore-radii distribution was determined after the DIN 66133 (1993) on sample fragments by mercury porosimetry using low (PASCAL 140) and high pressure (PASCAL 440) units from Thermo Fisher Scientific.

According to DIN EN ISO 12571 (2013), the hygroscopic water sorption was determined as well as the water vapor

### Table 3: Mixture for the Artik Rosa artificial replacement stone

| Starting Materials     | Mass in kg/m³ | Amount in g |
|------------------------|---------------|-------------|
| Cement CEM IV-A-LL 42.5 N | 485.9         | 465.9       |
| Trass Flour            | 30            | 30          |
| Aggregates 100%        | 943.4         | 943.4       |
| 0/0.25                 | 75.5          | 75.5        |
| 0.25/0.5               | 103.8         | 103.8       |
| 0.5/1                  | 103.8         | 103.8       |
| 1/2                    | 141.5         | 141.5       |
| 2/4                    | 217.0         | 217.0       |
| 4/8                    | 301.9         | 301.9       |
| Pigments 0.30%         | 0.30%         | 4.9         |
| Plasticizer 0.10%      | 0.10%         | 1.6         |
| Air entraining agent   | -             | -           |

Formulation for 1 dm³ Fresh Cement

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diffusion resistance (μ value) after DIN EN ISO 12572 (2017). Drill core samples with a diameter of 40 mm were used to analyze the uniaxial compressive strength. Flexural strength was determined after DIN EN 12372 (2007) on prisms with a dimension of 40*40*160 mm. Tensile strength was measured on disc-shaped samples with a length of 20 mm and a diameter of 40 mm based on the DIN 22024 (1989).

Surface hardness was determined by the DIN EN 12504-2 (2021) using a Schmidt hammer (equotip3) from the company PROCEQ.

The ultrasonic velocity was measured via direct transmission with a frequency of 350 kHz (DIN EN 14579, 2005). These data were used to calculate the dynamic Young’s modulus (Siegesmund and Dürrast 2014).

To characterize the weathering behavior of the stone restoration mortars and the artificial replacement stones, hydric and thermal expansion was determined on cylindrical samples (drill cores) with a length of 50 mm and a diameter of 5 mm following DIN EN 13009 (2000) and DIN EN 12370 (2020). Cubic samples were also used to evaluate the salt weathering resistance based on the DIN EN 12370 (2020).

**Stone restoration mortars and artificial replacement stones: results**

**Color adaptation and determination of the color composition**

To avoid stress in the contact area of the mortar and stone interface, a good correlation of the petrophysical properties is essential. Moreover, a visual evaluation of the replacement mortar or artificial stone is also fundamental, since an inappropriate color scheme would greatly affect the appearance of the monuments. A comparison of the different SRM samples shows that all binders could be colored by addition of pigments to such an extent that they correspond to the matrix color of the original rock. Color differences occur primarily due to the clasts contained in the rock, which were not reconstructed for the replacement mortars in favor of their processability. As shown in Fig. 5, different clasts and rock fragments influence the appearance of all rocks, which needs to be considered for further production processes. Besides a visual assessment, color measurements were carried out to obtain a numerical determination of the color valence. The evaluation of the color is carried out on the basis of the Lab Color System with L = lightness, a = red–green axis and b = blue–yellow axis. The ΔE value as a measure of the difference between two colors, calculated according to DIN 6174 (2007), can be used to quantify the differences between the SRM and the original tuff rock to be repaired. The smaller the ΔE value, the smaller the color difference between the SRM and tuff rock, which means that a small value indicates a good color matching. However, the ΔE value only gives a possible quantified subjective impression. As this system assumes a color equidistance which is not given (Heinisch 2011), the personal color sensation can differ. Nevertheless, as a quantification of the differences this value is appropriate in this case. The results show that the visual compatibility of the different SRMs varies in quality (Table 4).

Based on the above investigation, the samples CR CaO and CR CEM have the best color matching, whereas the samples CV CEM and SMA CEM have the worst value for SRMs. Generally, for all the stone replacement mortars the color matching can still be further optimized.

On the other hand, the quality of the colored artificial replacement stone depends on various influencing factors. Particularly decisive is the choice of the raw materials, especially that of the cement. White cement and gray cement have a clearly contrasting effect on the coloring of the concrete. The use of gray cement results in less bright colors than the use of white cement. The difference is more pronounced with lighter than with darker colors (Runge 2012).

To ensure that the coloration of the concrete to be produced corresponds as closely as possible to that of the original tuff, color series have been created. The aim was to match the appearance of the respective rock matrix with the cement paste and the fine aggregate to be reproduced. For this purpose, cubes with an edge length of 4 cm have been produced, consisting of water, gray cement and the respective 0/1 mm aggregate. Color pigments were added to the specimens in percentage gradations during the production.

For the color series of the Golden Armenia, oxide yellow was used exclusively, in proportions up to 1 wt. % (Fig. 6). The best result was obtained at 0.2 wt. %. Comparable color series were performed for the Artik Tuff, where the best

| Sample ID | L    | a     | b     | ΔE  |
|-----------|------|-------|-------|-----|
| CR        | 77.08| 12.46 | 5.64  |     |
| CR CEM    | 79.08| 14.87 | 5.09  | 3.2 |
| CV CEM    | 90.91| 0.69  | 7.77  | 9.3 |
| CV CaO    | 91.13| 1.13  | 5.47  | 7.2 |
| LOS       | 90.55| 0.48  | 2.65  |     |
| LOS CEM   | 88.67| 0.15  | –0.32 | 3.5 |
| LOS CaO   | 92.78| 0.48  | –1.77 | 5   |
| SMA       | 78.13| 8.46  | 5.29  |     |
| SMA CEM   | 86.9 | 10.17 | 2.12  | 9   |
| SMA CaO   | 82.78| 10.3  | 2.93  | 5   |

Table 4: Measured color values for each tuff variety and their respective replacement mortars and the color differences defined by ΔE

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result was achieved with the oxide red pigments at 0.3 wt.%. The pigment content of the concrete of the Gyumri Black and Sissian specimens was based on the Teipel (2020) color series for mortars. The first formula of the Sissian basalt was, therefore, mixed with 0.5 wt.% of black color pigments. For the artificial stone of the Gyumri Black, a 5 wt.% of the same pigment was added.

**Rock physical properties of stone restoration mortars**

The mechanical properties for all the stone replacement mortars (SRM) and the Mexican tuffs used as the selected source material are given in Table 5. All the mortar mixtures show differences to the tuff stone, but also to each other. All SRMs show porosities between 35.7% (CR CEM) and 46.1% (SMA CaO), while the respective CEM formulas show lower porosities. The porosities of the tuff stones vary between 40.8% (SMA) and 16.8% (LOS). Bulk densities of all CaO formulas are lower than the CEM mixtures (Table 5). The CEM mixtures are in a comparable range between 1.32 and 1.62 g/cm³. Tuffs show a higher variation between 1.52 (SMA) and 2.07 g/cm³ (LOS).

Generally, the mean pore radius of the CaO samples is larger than for the CEM samples (Table 5) varying between 0.18 µm and 0.39 µm (CaO) and CEM ranging 0.09 to 0.17 µm. The tuff source rocks show a greater variation and are largest for the SMA with 1.5 µm, while LOS and CV only show 0.04 µm. For the tuff stones, the trend with a larger mean pore radius, the percentage of micropores is lower (1.5 µm to 10 vol.% for SMA and 0.04 µm to 88 vol.% for CV). This may be transferred to the SRMs, while all CEM SRMs show a higher amount of micropores (35–51 vol.%) than the CaO samples (19–37 vol.%).

The pore-radii distribution shown in Fig. 7 indicates that the higher porosity of the CaO mortars in comparison to the CEM mortars is connected to a higher content of capillary pores. The CR CaO mortar has a distinct maximum of 10.7 vol.% (pore radius class: 0.63–1 µm), while 80 vol.% of all pores are capillary pores. The CR CEM mortar has a lower proportion of capillary pores (59 vol.%) and a low maximum of 4.9 vol.% (pore radius class: 0.25–0.4 µm). A comparable distribution can be found for the CR tuff (capillary pores of 64 vol.%; see Fig. 7). The CV CaO and CEM samples show a bimodal distribution of the pore radii (Fig. 7). A maximum of 4.8 vol.% at 0.4–0.63 µm and a submaximum of 4.4 vol.% at 0.01–0.015 µm were determined for the CEM mortar. In contrast, the CV tuff has a distinct maximum of 8.64 vol.% within the pore class of 0.1–0.16 µm. The proportion of capillary pores is very high for the CaO sample with 63 vol.%. The CEM mortar only shows 49 vol.%. The CV source rock contains 88 vol.% micropores.

The LOS mortars differ strongly from the LOS tuff pore-radii distribution. The LOS CaO mortar has a lower amount of micropores and a higher proportion of capillary pores (Fig. 7). The LOS CEM mortar has a uniform proportion of capillary pores (49 vol.%). In contrast, the LOS tuff has a micropore content of 85 vol.%. The SMA CaO sample shows a comparable distribution to the CR CaO formula. The pore class of 0.63–1 µm shows a maximum of 9.19 vol.% and capillary pores of 81 vol.%. SMA CEM mortar is a little lower with 7.1 vol.% in the pore class of 0.4–0.63 µm, with capillary pores of 65 vol.%. The SMA tuff shows a capillary pore proportion of 90 vol.% with a maximum of 15.38 vol.% (pore-radii class 2.51–3.98 µm; Fig. 7).

The capillary water uptake [kg/m²] for the LOS mortar is shown in Fig. 8. Tuff stones show the lowest water uptake. The CaO mortars show the highest water uptake, with a very fast uptake in comparison to the CEM samples. The w values of the mortars are lower for the CEM formulas and higher for the CaO formulas (Table 5).

The ultrasonic wave velocities of all SRMs range between 1.68 km/s (CV CaO) and 2.49 km/s (CR CEM). All tuff stones show comparable velocities with velocities of 2.6 km/s in the z-direction and slightly higher values in the x-direction (2.7–2.8 km/s). The LOS tuff is the exception with a strong anisotropy of 24% with 3.7 km/s in the x-direction and 2.8 km/s in the z-direction. All tuff stones show higher values of the dynamic Young’s Modulus than the SRMs, e.g., 8 MPa (SMA z-direction) and 28 MPa (LOS x-direction). The LOS tuff obtained...
### Table 5: Summary of the petrophysical properties and weathering behavior of the stone replacement mortars and the Mexican tuff source material

| Sample ID | SMA | SMA CEM | SMA CaO | CR | CR CEM | CR CaO | CV | CV CEM | CV CaO | LOS | LOS CEM | LOS CaO |
|-----------|-----|---------|---------|----|--------|--------|----|--------|--------|-----|---------|---------|
| Porosity [%] | 40.8 | 38.28 | 46.11 | 31.1 | 35.7 | 44.79 | 29.5 | 42.13 | 44.06 | 16.8 | 36.81 | 41.94 |
| Bulk density [g/cm³] | 1.52 | 1.53 | 1.38 | 1.78 | 1.57 | 1.39 | 1.54 | 1.32 | 1.24 | 2.07 | 1.62 | 1.51 |
| Particle density [g/cm³] | 2.57 | 2.48 | 2.56 | 2.58 | 2.45 | 2.52 | 2.18 | 2.28 | 2.22 | 2.49 | 2.56 | 2.6 |
| Water uptake vac [wt.%] | 27.0 | 25.05 | 33.39 | 18 | 22.69 | 32.15 | 19.0 | 31.97 | 35.46 | 8.0 | 22.79 | 22.79 |
| Water uptake atm. [wt.%] | 17.4 | 19.68 | 26.85 | 13.6 | 19.2 | 23.52 | 16.3 | 26.67 | 30.65 | 7.0 | 20.32 | 23.28 |
| s-value | 0.65 | 0.79 | 0.8 | 0.77 | 0.85 | 0.73 | 0.85 | 0.83 | 0.86 | 0.81 | 0.89 | 0.84 |
| Mean pore radius [µm] | 1.5 | 0.17 | 0.39 | 0.2 | 0.14 | 0.29 | 0.04 | 0.09 | 0.18 | 0.04 | 0.11 | 0.25 |
| Micro pores [%] | 10 | 35 | 19 | 36 | 36 | 20 | 88 | 51 | 37 | 85 | 48 | 25 |
| P-wave velocity [km/s] | | | | | | | | | | | | |
| X | 2.7 | 2.46 | 1.9 | 2.8 | 2.49 | 2.03 | 2.7 | 1.99 | 1.68 | 3.7 | 2.44 | 1.92 |
| Z | 2.6 | n.d | n.d | 2.6 | n.d | n.d | 2.6 | n.d | n.d | 2.8 | n.d | n.d |
| Young’s Modulus dyn [GPa] | 11 (x) 8 (z) | 9.3 | 5.1 | 14 (x) 12 (z) | 9.8 | 5.8 | 11 (x) 10 (z) | 5.3 | 3.6 | 28 (x) 16 (z) | 9.7 | 5.6 |
| Young’s Modulus stat [GPa] | 1.84 | n.d | n.d | 0.5 | 1.98 | 3.42 | 0.29 | 0.85 | 0.49 | 0.44 | 2.86 | 0.64 |
| Water uptake (w value) [kg/m²*√h] | | | | | | | | | | | | |
| X | 7.3 | 7.56 | 13.2 | 9.4 | 10.93 | 14.07 | 2.8 | 13.02 | 15.04 | 0.8 | 7.44 | 10.33 |
| Z | 4.7 | 8.34 | 10.9 | 7.1 | 6.02 | 12.05 | 2.6 | 11.82 | 17.39 | 0.7 | 6.91 | 12.0 |
| Surface hardness [HL] | | | | | | | | | | | | |
| Dry x | 402.3 | 333.2 | 340.65 | 403.2 | 317.36 | 306.8 | 510.35 | 296.1 | 282.35 | 447.7 | 294.05 | 339.25 |
| Z | 432 | n.d | n.d | 364.75 | n.d | n.d | 528.4 | n.d | n.d | 444.38 | n.d | n.d |
| Hydric expansion [mm/m] | | | | | | | | | | | | |
| X | 0.07 | 0.63 | 0.53 | 0.1 | 0.67 | 0.7 | 1.39 | 1.98 | 1.89 | 0.58 | 1.25 | 1.09 |
| Z | 0.23 | n.d | n.d | 0.24 | n.d | n.d | 1.68 | n.d | n.d | 1.22 | n.d | n.d |
| Flexural strength [N/mm²] | n.d | 3.71 | 1.46 | n.d | 4.19 | 1.49 | n.d | 1.79 | 0.66 | n.d | 2.63 | 1.94 |
| Tensile strength [N/mm²] | | | | | | | | | | | | |
| X | 3.9 | n.d | n.d | 6.1 | n.d | n.d | 3.4 | n.d | n.d | 6.3 | n.d | n.d |
| Z | 4 | n.d | n.d | 4.7 | n.d | n.d | 3.0 | n.d | n.d | 8.3 | n.d | n.d |
| Water vapor diffusion [µ] | | | | | | | | | | | | |
| X | 7.37 | 10.41 | 8.3 | 7.47 | 10.21 | 7.51 | 9.2 | 9.22 | 11.74 | 27.93 | 9.39 | 7.56 |
| Z | 8.1 | n.d | n.d | 8.39 | n.d | n.d | 10.1 | n.d | n.d | 13.41 | n.d | n.d |
| Sorption 95% rh [wt.%] | 3.6 | 5.38 | 4.51 | 1.2 | 6.26 | 5.3 | 3.4 | 9.81 | 9.63 | 1.6 | 6.11 | 4.76 |
| Thermal expansion [mm/m] | | | | | | | | | | | | |
| coefficient α | | | | | | | | | | | | |
| X | 8.81 | –0.93 | –1.24 | 8.43 | –3.6 | –3.53 | 7.95 | –13.21 | –10.77 | 9.62 | –3.91 | –2.16 |
| Z | 9.31 | n.d | n.d | 8.42 | n.d | n.d | 9.03 | n.d | n.d | 10.56 | n.d | n.d |
| 2. Cycle thermal expansion [mm/m] | 8.61 | 9.52 | 9.6 | 9.16 | 8.95 | 8.83 | –1.55 | 8.31 | 8.26 | 9.97 | 9.91 | 9.26 |
| 9.23 | 9.11 | –1.99 | | | | | | | | | | |
by far the highest values with a high anisotropy of 43%. The CEM-based mortars show higher values than the CaO mortars (Table 5).

The surface hardness of all CEM and CaO mortars ranges between 282.35 (CV CaO) and 340.7 (SMA CaO). The differences between the CEM and CaO mortars are very low with no direct dependence on the respective binder. The highest surface hardness of the tuff stones was measured for the CV tuff with 510 and the lowest for SMA with 402.

The hydric expansion of all mortars is 0.53 mm/m for SMA CaO and 1.98 mm/m for CV CEM (Fig. 9), while the differences between the binders in the respective tuff mixtures are small. Greater differences occur in the different source rocks.

For the LOS tuff, the observed directional dependence is also detected for the hygric expansion. The highest expansion was measured for the CV tuff (1.39 mm/m), while the SMA shows the lowest expansion (0.07 mm/m). For the SMA mortars, the lowest expansion was determined in SMA CEM (0.63 mm/m) and 0.53 mm/m in SMA CaO. The highest for the CV mortars is 1.98 mm/m (CEM) and 1.89 (CaO).

The measured water vapor diffusion resistance shows almost no differences between the mortar formulas or the tuff source rocks (Table 5). All values range between 7.6 µm (LOS CaO) and 11.7 µm (CV CaO) for the mortar mixtures and 7.4 µm (SMA) to 10.1 µm (CV) for the tuff stones. The LOS tuff is the exception since the values range between 13.4 µm (z-direction) and 27.9 µm (x-direction). The values here are higher than for the other Mexican tuffs because the directional dependence is also clearly pronounced with an anisotropy of 52%.

The flexural strength of all binder-tuff stone formulas differ within both binder combinations as well as within the tuff stone additives (Table 5). Generally, the CaO formulas show lower values than the CEM mixtures, 0.66 N/mm² for CR CaO and 1.9 N/mm² for LOS CaO. The CEM formulas vary between 1.79 N/mm² (CV CEM) and 4.19 N/mm² (CR CEM). The lowest difference between the two binders was analyzed for the LOS mixtures. For the tuffs, the tensile strength was analyzed for comparative purposes and also characterized in terms of its directional dependence. The values range between 3.0 MPa (CV z-direction) and 8.3 MPa (LOS z-direction). The highest anisotropy was determined for the LOS tuff (24%) and the CR tuff (23%). In the x-direction, however, the CR anisotropy is higher than in the z-direction.

The uniaxial compressive strength (UCS) was determined for all samples except for the SMA CEM (Table 5). The results for the mortars differ between the CaO and CEM mixtures as well as for each source rock. Generally, the CaO formulas show lower values than the CEM mixtures, e.g., LOS CaO (1.74 MPa) and CV CEM (4.97 MPa). The source
rocks have much higher values, e.g., 17.42 MPa (CR) and 40.56 MPa (LOS). The static Young’s Modulus, based on the UCS measurement shows the same trend for the mortars, with lower values for the CaO formulas (0.14 GPa (LOS CaO) – 0.50 GPa (SMA CaO), and higher values for the CEM formulas (0.49 GPa (CV CEM) – 3.42 GPa (CR CEM)). The tuff source rocks show 0.85 GPa for the CV tuff and 2.86 GPa for the LOS tuff. In summary, the static Young’s Moduli are much lower than the dynamic ones.

Sorption was determined in terms of percent weight gain by increasing humidity from 25 to 95% in 10% increments and is shown in Fig. 10. The total amount of water absorbed after 95% relative humidity is listed in Table 5 and shows that the sorption of the SRMs is generally higher than the values of the tuff source rocks. The sample set with the highest sorption values is the CV set, with 9.81% for the CEM.

Fig. 7 Pore radii distribution comparing the Mexican tuff rocks to the CaO and CEM stone replacement mortars

Fig. 8 Capillary water uptake [kg/m²] in the x- and z-direction for the Loseros tuff (LOS) and the respective LOS CaO mortar and the LOS CEM mortar during a 24 h period
and 9.63% for the CaO. The SMA mortars showed the lowest weight gain, i.e., 5.38% (CEM) and 4.51% (CaO). In contrast, the SMA tuff exhibits the highest weight gain with 3.6% and the CR tuff the lowest with 1.2%. In general, the highest weight gain occurs by increasing the relative humidity from 85 to 95% (Fig. 10).

The thermal expansion coefficient $\alpha \left[10^{-6} \, K^{-1} \right]$ is calculated from the slope of the strain curve and represents the thermal expansion of a material within a specific range of temperatures. All SRM mortars show negative values in the first cycle due to contraction, e.g., $-0.93 \left[10^{-6} \, K^{-1} \right]$ for SMA CEM and $-13.21 \left[10^{-6} \, K^{-1} \right]$ for CV CEM (Table 5). The second cycle is characterized by a positive value, which is comparable for all mortars, independent of the mortar formula varying between $8.26 \times 10^{-6} \, K^{-1}$ (CV CaO) and $9.91 \times 10^{-6} \, K^{-1}$ (LOS CEM). All tuff stones range between $7.95 \left[10^{-6} \, K^{-1} \right]$ (CV, x-direction) and $9.86 \times 10^{-6} \, K^{-1}$ (LOS, x-direction). Contrary to the previous results, the LOS tuff does not show any pronounced anisotropy, whereas the CV tuff shows the highest anisotropy with 12%. The maximum expansion [mm/m] is the highest for the LOS tuff (0.75 mm/m) and the lowest for the CV tuff (0.53 mm/m). Here, the SRM with the almost lowest expansion coefficient shows the highest expansion (CV CEM 0.59 mm/m), while the CR CEM and CaO show the lowest expansion with 0.21 mm/m. The mortar formulas show almost no difference in values of expansion or the coefficient, except in the first cycle, where all SRMs show a different intensity of the negative $\alpha$ coefficient (Table 5).
Rock physical properties of the replacement stones

The effective porosities of the artificial replacement stones (i.e., concrete mixtures) range from 13.9 to 37.4% (see Table 7). ARB2 and ARB1 show the highest values, followed by GAB1 and GAB2 with 21.9 and 22.2%. The porosity of the Gyumri Black concrete specimens is slightly lower (21.9 and 22.2%). The Sissian basalt showed the lowest values.

The matrix densities of the concrete varieties range from 2.46 to 2.75 g/cm³. The highest values for the Sissian concrete show values of 2.64 to 2.75 g/cm³. GYB1 and GYB2 have the lowest matrix density with 2.46 g/cm³. Matrix densities for ARB1 and ARB2 and GAB1 and GAB2 are similar with 2.52 to 2.54 g/cm³.

Bulk densities for concrete samples exhibit a wider range between 1.59 and 2.32 g/cm³. ARB1 and ARB2 show the lowest values (Table 6). In contrast, bulk densities for the Sissian concrete are significantly higher with values of 2.24 and 2.32 g/cm³.

The mean pore radius and amount of micropores and capillary pores are listed in Table 7. The average pore size is between 0.04 and 0.28 µm. ARB1 and ARB2 have by far the largest mean pore radii at 0.27 and 0.28 µm. The Gyumri Black and Golden Armenia concretes show average pore sizes of 0.06 to 0.09 µm. The smallest mean pore radius was measured on sample SIB3. With the exception of two Artik concrete samples, the proportion of micropores dominates in GAB1 (55.6) up to 84.9% (SIB3).

Figure 11 shows the pore-radii distribution for the artificial replacement stones. The pore class distribution ranges from 0.04 to 3.98 µm. ARB2 shows a bimodal distribution with a maxima between 0.10 and 0.16 µm and 1.00 and 2.51 µm. Pore classes with radii larger than 10 µm account for a larger proportion of the total porosity in ARB2 than in ARB1. GAB1 and GAB2 show a maximum at 0.04 to 0.10 µm and is more pronounced in GAB2. Capillary pores show a range up to 63.1 µm in GAB2. The largest pore radii in GAB1 reaches a size up to 2.51 µm.

The pore radius distribution for GYB1 and GYB2 (Fig. 11) shows a pore size maximum in the micropore range between 0.016 and 0.063 µm and a submaximum in the capillary pore range of 0.63 and 1.58 µm. GYB2 shows a higher percentage of total porosity compared to GYB1 with radii smaller than 0.01 m and larger than 3.98 µm. The pore-radii distribution for SIB1 and SIB3 show a significant pore

| Table 6 | Summary of the petrophysical properties and weathering behavior of the investigated artificial replacement stones using Armenian tuffs as a source material |
|-------------------------------------|-------------------------------------|
| **Sample ID** | **ARB1** | **ARB2** | **GAB1** | **GAB2** | **SIB1** | **SIB2** | **SIB3** | **GYB1** | **GYB2** |
| Porosity [%] | 35.3 | 37.4 | 29.5 | 28.3 | 14.0 | 15.7 | 15.3 | 22.0 | 22.2 |
| Bulk density [g/cm³] | 1.63 | 1.59 | 1.78 | 1.81 | 2.27 | 2.32 | 2.24 | 1.92 | 1.92 |
| Particle density [g/cm³] | 2.53 | 2.54 | 2.52 | 2.52 | 2.64 | 2.75 | 2.64 | 2.46 | 2.46 |
| Water uptake vac [wt. %] | 21.6 | 23.5 | 16.6 | 15.6 | 6.2 | 6.8 | 6.9 | 11.4 | 11.6 |
| Water uptake atm. [wt. %] | 12.6 | 11.4 | 11.8 | 10.3 | 4.7 | 4.3 | 4.3 | 7.0 | 6.5 |
| s value | 0.58 | 0.48 | 0.71 | 0.66 | 0.76 | 0.63 | 0.62 | 0.61 | 0.56 |
| Mean pore radius [µm] | 0.27 | 0.28 | 0.09 | 0.08 | 0.06 | 0.14 | 0.04 | 0.08 | 0.06 |
| Micropores [%] | 32.5 | 34.6 | 55.6 | 56.7 | 79.7 | 56.3 | 84.9 | 60.9 | 68.7 |
| Capillary pores [%] | 67.5 | 65.4 | 44.1 | 43.3 | 20.4 | 43.8 | 15.1 | 39.1 | 31.4 |
| P-wave velocity [km/s] | 3.09 | 3.06 | 3.56 | 3.76 | 4.18 | 4.08 | 4.18 | 3.92 | 3.84 |
| Young’s Modulus dyn [GPa] | 16.7 | 14.9 | 20.9 | 19.4 | 37.0 | 38.3 | 34.6 | 27.4 | 25.4 |
| Young’s Modulus stat [GPa] | 4.1 | 4.5 | 4.8 | 4.8 | 7.1 | 7.0 | 6.5 | 6.6 | 6.1 |
| Water uptake (w value) | 2.6 | 2.0 | 2.4 | 2.0 | 1.0 | 0.7 | 1.0 | 1.2 | 1.8 |
| Surface hardness [HL] | 437 | 497 | 510 | 500 | 648 | 625 | 621 | 637 | 602 |
| Hydric expansion [mm/m] | 0.59 | 0.45 | 0.87 | 0.82 | 0.61 | 0.49 | 0.58 | 0.49 | 0.49 |
| Flexural strength [N/mm²] | – | 5.0 | – | 7.1 | – | 8.3 | 9.5 | n.d | 7.7 |
| Compressive strength [MPa] | 35.9 | 38.9 | 42.7 | 40.7 | 76.1 | 66.4 | 61.1 | 57.5 | 54.2 |
| Sorption 95%rh [wt. %] | 4.5 | 4.3 | 4.4 | 5.1 | 3.1 | 3.0 | 3.7 | 3.9 | 4.0 |
| Thermal Exp. Coefficient α | 8.16 | 7.27 | 8.58 | 8.0 | 8.81 | 7.88 | 8.26 | 9.04 | 8.28 |
| Thermal Exp. 2nd cycle | 5.6 | 5.27 | 5.98 | 4.61 | 6.27 | 6.97 | 7.19 | 7.22 | 6.73 |
| Residual strain [mm/m] | | | | | | | | | |
| Dry | –0.27 | –0.29 | –0.34 | –0.51 | –0.2 | –0.19 | –0.24 | –0.16 | –0.16 |
| Wet | 0.91 | 0.59 | 0.82 | 0.81 | 0.87 | 0.19 | 0.23 | 0.55 | 0.27 |
| Material loss [wt. %] | | | | | | | | | |
| After 56 cycles | 6.91 | 0.04 | 4.24 | 0.11 | 2.32 | – | <0.01 | 12.68 | 0.81 |
size maximum in the micropore range between 0.025 and 0.040 µm. Both concrete types show unoccupied pore radius groups in the range of capillary pores larger than 2.51 µm. In sample SIB3 there are no pore spaces between 2.51 and 15.84 µm, but with a size increase up to 63.10 µm they are present again.

The water absorption value in vacuum varies from 6.2 wt.% (SIB1) to 23.5 wt.% (ARB2). In contrast to the bulk densities, the percent weight increase for the ARB1 and ARB2 samples are the greatest, and for the Sissian concrete the least. In contrast, the concrete cubes of Golden Armenia and Gyumri Black show mean water absorption values of 16.6 and 15.6 wt.% as well as 11.4 and 11.6 wt.%, respectively. The exception is the Golden Armenia concrete, where the weight increase from formula 1 to 2 is greater (see Table 6).

The water absorption value in vacuum varies from 6.2 wt.% (SIB1) to 23.5 wt.% (ARB2). In contrast to the bulk densities, the percent weight increase for the ARB1 and ARB2 samples are the greatest, and for the Sissian concrete the least. In contrast, the concrete cubes of Golden Armenia and Gyumri Black show mean water absorption values of 16.6 and 15.6 wt.% as well as 11.4 and 11.6 wt.%, respectively. The exception is the Golden Armenia concrete, where the weight increase from formula 1 to 2 is greater (see Table 6).

Under atmospheric conditions, the amount of water absorbed for all specimens is lower than in vacuum. The values range from 4.3 to 12.6 wt.%. In a vacuum the Sissian concrete absorbs the lowest amount of water in weight percent (4.3 to 4.7 wt.%). GYB1 and GYB2 have a slightly higher value of 7.0 and 6.5 wt.%. Compared to the initial weight, the Artik and Golden Armenia concretes absorb the most water. The values for ARB1 and ARB2 are 12.6 and 11.4 wt.%, and for GAB1 and GAB2 16.6 and 15.6 wt.%. For all samples, the value of the modified mixture is lower than for the first concrete series.

The s values of the concrete specimens range from 0.48 to 0.76. All concrete cubes have lower values than 0.75 with the exception of SIB1 (Table 6). This is an indication that frost resistance may be present. The Artik Rosa and Gyumri concrete samples have the lowest s values (Table 6). Optimized concrete varieties all show lower results than for the first mixture. This may indicate that the modified concrete formulas are somewhat more resistant to freeze–thaw exposure.

Table 6 shows the w values of the capillary water absorption ranging from 0.7 to 2.4 kg/m²h⁰.5. The path of the demineraled water absorption during the test period is shown in Fig. 12. The highest water absorption with w values (between 2.0 and 2.6 kg/m²h⁰.5) were determined in the Artik and Golden Armenia concrete samples. The Sissian concrete samples show a comparable behavior to the Gyumri Black concrete, however, the difference that after 24 h the curves are still slightly increasing. The w values of the Sissian and Gyumri Black concrete varieties are lower than those of the Artik and Golden Armenia concretes (Table 6).

The water vapor diffusion resistance of the tested specimens ranges from 15.0 up to 71.5 µ (Table 6). The µ values of the Sissian concrete are by far the highest with 52.2 (SIB2 and SIB3) and SIB1 with 71.5. The lowest values were obtained for the samples ARB2 with 15.0 and GAB2 with 17.6. Somewhat higher resistivities were obtained for 18.1 (ARB1) and 21.2 (GAB1). The Gyumri Black concrete is in the middle range with 32.5 for the GYB1 and 33.1 for the GYB2. All specimens show a decrease of the water vapor diffusion resistance with the exception of the Gyumri concrete samples.

The range of sorption values determined by means of the climatic chamber method at a relative humidity (rh) of 95% are shown in Table 6. With 3.0 to 3.7 wt.% and with 3.9 and 4.0 wt.% the results of the Sissian and Gyumri Black

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| Property                      | Requirements | SMA CEM | CaO  | CR SEM | CaO  | CV CEM | CaO  | LOS SEM | CaO  |
|-------------------------------|--------------|---------|------|--------|------|--------|------|---------|------|
| Porosity (%)                  | ≥100%        | 38.28   | 46.11| 35.7   | 44.79| 42.13  | 44.06| 36.81   | 41.94|
| Bulk density (g/cm³)          | 50-150%      | 1.53   | 1.38 | 1.57   | 1.39 | 1.32   | 1.24 | 1.62    | 1.51 |
| Particle density (g/cm³)      | 50-150%      | 2.48   | 2.56 | 2.45   | 2.52 | 2.28   | 2.22 | 2.56    | 2.56 |
| Water uptake (vac) (wt%)      | 50-150%      | 25.05  | 33.39| 23.69  | 32.15| 31.97  | 35.46| 21.79   | 22.79|
| Water uptake (atm) (wt%)      | 50-150%      | 19.68  | 26.85| 19.2   | 23.52| 26.67  | 30.65| 20.32   | 23.28|
| Mean pore radius (µm)         | As small as possible | 0.17   | 0.39 | 0.34   | 0.29 | 0.09   | 0.18 | 0.11    | 0.25 |
| Micropores (%)                | As small as possible | 35     | 19   | 41     | 20  | 51     | 37  | 48      | 25  |
| w-value                       | 50-100%      | 7.56   | 13.2 | 10.93  | 14.07| 13.02  | 15.04| 7.44    | 10.33|
| Water vapor diffusion (µ)     | 50-100%      | 10.41  | 8.3  | 10.21  | 7.51 | 9.22   | 11.74| 9.39    | 7.56 |
| Sorption 95% rh (wt%)         | 50-150%      | 5.38   | 4.51 | 6.26   | 5.3  | 9.81   | 9.63 | 6.11    | 4.76 |
| P-wave velocity (km/s)        | 50-150%      | 2.46   | 1.9  | 2.49   | 2.03 | 1.99   | 1.68 | 2.44    | 1.92 |
| Young’s Modulus dyn (GPa)     | ≤ 80%        | 9.3    | 5.1  | 9.8    | 5.8  | 5.3    | 5.6  | 9.7     | 5.6  |
| Surface hardness (LH)         | 50-150%      | 333.2  | 340.65| 317.36| 306.8| 296.1  | 282.35| 294.05  | 339.25|
| Flexural strength (N/mm²)     | ≤ 80%        | 3.71   | 1.46 | 4.19   | 1.49 | 1.79   | 0.66 | 2.63    | 1.94 |
| UCS (dry) (MPa)               | ≤ 60%        | ---    | 3.57 | 11.34  | 2.13 | 4.97   | 4.01 | 6.48    | 1.74 |
| Hydric expansion (mm/m)       | 50-150%      | 0.63   | 0.53 | 0.67   | 0.7  | 1.98   | 1.89 | 1.25    | 1.09 |
| Thermal expansion (mm/m)      | 50-150%      | 0.32   | 0.32 | 0.21   | 0.21 | 0.59   | 0.48 | 0.24    | 0.24 |

The respective petrophysical properties are listed for each stone replacement mortar, the required reference values in column 2 and the specifications for the mortar formulas CEM and CaO for the corresponding tuff. Green colored properties meet the requirements, red colored properties mismatch, while orange colors do not exactly meet the requirements, but within a negligible amount.

Table 7 Color-coded stone replacement mortars with regard to their suitability according to Snethlage and Pfanner (2020)
Fig. 11 Pore radii distribution for the artificial replacement stones using Armenian tuffs as the source rock
Concrete formulas are the lowest. The hygroscopic sorption is strongest in the Golden Armenia mixtures. Somewhat lower values are shown by specimens ARB1 and ARB2 with 4.5 and 4.3 wt.%, respectively. The change in the concrete formulas resulted in an increase in hygroscopic sorption for all specimens, except for the Artik Rosa concretes.

The weight increase of the test samples due to an increase in relative humidity (sorption curves) is shown in Fig. 13. The sorption behavior is quite similar for all concrete specimens. Up to about 85% r.h. there is a growing increase in the mass of the specimens. When increasing to 95% r.h., all concrete specimens show a weight increase compared to the lower humidities. Golden Armenia and Artik Rosa concrete samples show the highest sorption values over the entire test period. The sorption effect for the Sissian concrete is lower than for the other specimens, especially at higher relative humidities of 65% and above.

The ultrasonic velocities of the concrete specimens range from 3.06 km/s and 4.18 km/s (Table 6). The results for the Sissian concrete are the highest with values of 3.92 km/s to 4.18 km/s. ARB1 and ARB2 show the lowest velocities (i.e., 3.09 km/s and 3.06 km/s). Moderate velocities were measured in the Golden Armenia and Gyumri Black mixtures, (i.e., 3.27 km/s and 3.84 km/s). Adjusting the mixing formula resulted in a decrease of the ultrasonic velocities for all varieties.

The compressive strength values of the different concrete specimens are listed in Table 6. The Artik Rosa (ARB1 and ARB2) show the lowest values of 35.9 MPa and 38.9 MPa, respectively. The highest compressive strength values were measured in the Sissian Basalt concrete (see Table 6). Golden Armenia concrete show a lower range of strength values (Table 6). The Gyumri Black concrete achieved somewhat higher values (57.5 MPa for GYB1 and 54.2 MPa for GYB2).

The dynamic modulus of elasticity range from 14.9 GPa (ARB2) to 38.3 GPa (SIB2). With results averaging about 35.0 GPa, the basalt concrete varieties show the highest results (Table 6). Somewhat lower are the dynamic moduli of elasticity of the Golden Armenia and Gyumri samples.
(about 20.0 GPa and 26.0 GPa, respectively). The Artik concrete showed the lowest values with 14.9 GPa and 16.7 GPa, respectively.

The static Young’s modulus ranges from 4.1 GPa (ARB1) to 7.1 GPa (SIB1), and thus are significantly lower than the values of the dynamic Young’s modulus. The basalt concrete again shows the highest deformation values of 6.5 GPa and 7.1 GPa. The results of the Gyumri concrete are 6.6 GPa and 6.1 GPa, and the GAB1 and GAB2 specimens show a value of 4.8 GPa. The lowest are the Artik concrete with 4.1 GPa and 4.5 GPa.

The rebound hardness test (surface hardness) on the concrete test specimens range from 437 for ARB1 to 648 for SIB1 (Table 6). The Gyumri Black and Sissian concrete samples are above 600. Golden Armenia concrete has a mean hardness value of around 500. The means for the Artik replacement stones gave a surface hardness of 437 for ARB1 and 497 for ARB2 (Fig. 14). The hardness values of the second concrete mixtures have slightly decreased values, with the exception of ARB2.

Table 6 also shows the results of the flexural strength test carried out on the second and third concrete mixtures. The results range from 5.0 to 9.5 MPa. ARB2 and GAB2 are the lowest with 5.0 and 7.1 MPa. A slightly higher flexural strength was measured in GYB2 with 7.7 MPa. The highest measured values were measured in the Sissian Basalt concrete with 8.3 (SIB2) and 9.5 MPa (SIB3).

The maximum values of the hydric strain tests are listed Table 6. Golden Armenia concrete shows the highest with 0.87 (GAB1) and 0.82 mm/m (GAB2). All other specimens range from 0.49 to 0.61 mm/m. Modifying the concrete mixture tended towards a slight reduction in the hydric strain. The largest decrease occurred between ARB1 and ARB2 at 0.14 mm/m. For the Gyumri Black concrete there was no change in hydric strain.

All concrete specimens show a pronounced hydric expansion, which mainly takes place within the first 2 h (Fig. 15). After about 6 h most of the samples reach a plateau, which is maintained until the end of the test period. The increase in expansion during this period is very small compared to the first 2 h.

The thermal expansion coefficients for the first cycle of the replacement stones are $7.27 \times 10^{-6}$ K$^{-1}$ and $9.04 \times 10^{-6}$ K$^{-1}$ (Table 6). Values of the second and third cycle are smaller (Table 6). The expansion behavior of all specimens over the course of the three drying cycles is shown in Fig. 16.

In the dry state, all specimens show an increasing pronounced contraction (see Table 6). The contraction of the concrete specimens ranges from – 0.16 mm/m to – 0.51 mm/m. Comparing the results of the first, second, and third series of specimens shows that there are no major deviations between them.
Fig. 16  Thermal dilatation $\varepsilon$ for the artificial stone replacement samples and the water–cement cylinder as a function of the temperature.

Fig. 17  Plot of the residual strain for the artificial stone replacement samples and the water–cement cylinder as a function of temperature cycles in the dry and wet states.
The flooding of the specimen chamber and the subsequent thermohydric cycles results in a strong residual strain (Fig. 17). All residual elongation took place in the first two wet cycles for the core samples of the first mixtures. ARB1 and SIB1 show the largest change in their length under wet conditions at about 0.9 mm/m. GYB1 has the lowest with 0.55 mm/m. The second test series samples show a residual strain in the range of 0.19 mm/m and 0.81 mm/m. SIB2 and SIB3 only show an increase in their length after the first wet cycle. In contrast, all other concrete samples showed a constant increase in length during the wet cycles.

After only 10 freeze–thaw cycles, the samples ARB1, GAB1, and GYB1 already showed a significant weight loss of 1.9 to 5.7% compared to the wet weight before the first thermal loading, which started at about the 7th cycle. Like the other cubes, the specimen SIB1 also showed signs of weathering at the edges and adjacent surfaces but only to a minor extent. The loss of material in this case was roughly in line with the continued progressive mass absorption of the salt solution. After about 20 freeze–thaw cycles, the samples ARB1, GAB1, and SIB1 stabilized and remained approximately constant until the end of the experiment after 56 cycles. For these cubes, the loss due to fragment breakout increased only to a small extent from the 14th cycle onward. GYB1 showed by far the greatest weight loss during the 7th and the 20th cycle.

Weathering on all specimens occurred in the form of small rectangular to elongated and partly oval fragments on the surface, which had a length and width of about 1 to 8 mm and had a thickness of up to 2 mm. Back-weathering in sample GYB1 took place in some places not only close to the surface, but also in a second weathering plane.

After 56 cycles the percentage mass loss due to weathering for specimen SIB1 was 2.32%. This concrete mix can thus be considered as frost resistant, as it is below the 3% criterion (Table 6). The three tuff varieties have a weathering of, in part, significantly more than 3 wt.% and are thus, with respect to the exposure class XF4, to be considered as insufficiently frost resistant. The mass loss of sample GYB1 is particularly high, corresponding to 12.7% of the initial weight of the concrete cube.

The initial weight increase of the specimens of the second and third concrete mixture is roughly comparable to that of the first specimens. The SIB2 cube is an exception, since it shows by far the smallest increase in weight with 0.9 wt.%. GAB2 and GYB2 take up slightly less de-icing salt solution at the beginning than their equivalents of the first series of samples. Up to about the 10th cycle, all cubes continuously increase in mass. Until the end of the measurement, the masses of samples GAB2, ARB2, and SIB3 remain relatively constant without significant changes. SIB3 showed no weathering of fragments and no considerable percentage mass loss and can thus be considered frost resistant. GAB2 and ARB2, with weathering of 0.11 wt.% and 0.04 wt.%, respectively, are also well below the limit value of 3 wt.%. Slightly more material loss was observed for sample GYB2 (ca. 4.55 g), which is 0.81% of the initial mass. The Gyumri concrete can be considered as frost resistant. In contrast, all other test specimens, e.g., the second Sissian concrete exhibits the formation of cracks during the test and finally breaks open after the 8th cycle. Thus, this can be considered as not frost resistant.

**Weathering behavior of tuffs and stone replacement mortars**

Various investigations were carried out to determine the weathering behavior in the source rocks and SRMs. First the saturation coefficient (s value) was analyzed to describe the frost resistance. The amount of pore space accessible for the water adsorption is described by the saturation coefficient (S). This is an important parameter, as a higher water content in the rock can result in a higher risk of taking damage due to ice crystallization (Siegesmund und Dürrast 2014). After Hirschwald (1912), values < 0.75 point to weathering and frost resistant rocks. The frost resistance is uncertain until further investigations for rocks with values between 0.75 and 0.9. Rocks with s values > 0.9 are classified as not weathering and frost resistant. The s values listed in Table 5 indicate, that with the exception of the SMA tuff, all materials show values between 0.75 and 0.9, and are, therefore, classified as uncertain with regard to their frost resistance. Following this classification, the SMA tuff is a weathering resistant rock. These data correlate well with the salt weathering results, which show that the SMA tuff lasted more than 85 salt cycles (Fig. 18). The decay potential of salt crystallization depends on the pore-radii distribution. According to Ruedrich and Siegesmund (2007), a unimodal distribution is particularly susceptible to salt weathering. Furthermore, crystallization pressure occurs in the pore sizes smaller than 30 nm (Rijniers et al. 2005) or 50 nm (Steiger et al. 2014). The CV shows the lowest salt weathering resistance, since 15 cycles caused a minimum weight loss of at least 30% (according to DIN EN 12,370, 2020; Fig. 18). The mortar formulas show a good salt weathering resistance. The exception is the LOS CEM, which deteriorated after 20 cycles. All the SRMs samples are less vulnerable in comparison to the source rocks. LOS mortars show the worst salt resistance (Fig. 18). They disintegrated the first, independent of the binder. All the other mortar samples survived at least 82 cycles of salt weathering, while the CR CaO deteriorated after 51 cycles.
**Discussion**

**Comparison of tuff rock und stone replacement mortar**

According to the formulated quality tests for stone replacement mortars by Snethlage and Pfanner (2020), the SRMs are required to attain petrophysical properties that are comparable to the original stone. In Table 7, the respective requirements and the mortar measuring results are listed and color-coded with regard to their suitability for the requirements according to Snethlage and Pfanner (2020).

The direct comparison of all results shows that the density, ultrasonic velocity, surface hardness, flexural strength, the uniaxial compressive strength, and the thermal expansion results of all mortars meet the requirements. Based on these data, the CR CEM formula shows the best suitability, followed by the SMA formulas and the CR CaO samples, while the LOS shows the largest deviations with regard to the original stone. This suitability is only based on the number of mismatches, with regard to the requirements.

The porosities of the tuff stones vary between 40.8% (SMA) and 16.8% (LOS), whereas the porosities of the LOS SRM samples do not meet the required variation range of more than 100%. With regard to the purpose of a stone replacement mortar, the SRMs should be more porous than the original stone. Thus, water transport and dehydration are preferably taking place in the mortar and consequently any salt and ice crystallization does not take place in the rock. With regard to this property, all SRMs fulfill this aspect, except the SMA CEM, whereby the reduction of the mortar is very low and negligible.

The SMA CEM and CaO, as well as the CR CEM samples meet the requirements for the water uptake under vacuum, while the atmospheric water uptake of the SMA CaO is a little too high. The mean pore radius of the SMA and CR samples fit the requirements independent of the binder. The amount of micropores is for all samples smaller than for the tuff rock, with the exception of the SMA formulas.

The $w$ values for the CR and SMA CEM samples are almost within the tolerance span for SRMs, while all the other samples show to high $w$ values in comparison to their original stone. The samples SMA CEM and CR CEM show a water vapor diffusion resistance which is too high and above the 100% requirement. The sorption of the SMA is within the range of requirements, while all the other samples show a hygric sorption above 150% in comparison to the respective tuff stone. With the exception of the SMA CEM sample, all the Young’s Moduli of the SRMs are good, with regard to the requirement of values smaller than 80% of the original stone. As this parameter is primarily used to evaluate the replacement mortars (Snethlage and Pfanner 2020), this is a good result for the formulas as these mortars generally achieve lower Young’s Moduli as the original stone, to avoid possible damage from the original rock. The values of the hydric expansion are for the CV SRMs within the tolerance span of the CV tuff, the LOS mortar formulas mismatch in one direction, which needs to be considered as this stone shows a high directional dependency of the rock properties.

On basis of these data, it can be concluded that especially the properties for the water transport show discrepancies with regard to the specific tuff rock. Both water absorption and water vapor diffusion ensure a balanced moisture balance between mortar and stone, and are decisive for the durability of the applied mortar (Snethlage and Pfanner 2020). The evaluation of the thermal and thermohygric strain shows that all mortars, in relation to their corresponding parent rock, always exhibit significantly higher residual strain. Overall, the residual strain of all mortars are to be considered critical, since large differences between parent rock and mortar leads
to stress and finally to a loss of material. The mortars react very sensitively at very high temperatures (> 80 °C). Therefore, in relation to practical application, it must be questioned whether the mortars really have to withstand such a high load. Both, the expansion, and the shrinkage behavior of the mortar under the influence of temperature and moisture should be adapted as well as possible to the original rock. The better the adaptation of the mortar to the original rock, the lower the stresses occurring at the interfaces. The associated losses in terms of durability can lead to the detachment of the mortar. Since the $\alpha$-expansion coefficients are compared with each other, it can be seen that all mortars meet the requirements. Nevertheless, the residual expansion amounts should be considered for critical evaluation.

**Comparison of source rock and artificial replacement stones**

**Visual properties**

Comparing the optical appearance of the concrete bodies to the respective stone is very important for evaluating the success of the mixture development. The original appearance of the building should not be affected by the use of the replacement stone and the visual difference between the different materials should be minimal.

The coloration of the cement pastes of the Artik replacement stone corresponds very well to the matrix of the tuff (Fig. 19A). A closer inspection of the concrete samples shows that the aggregate is a little darker than the colored cement paste. The plagioclase phenocrysts are up to a few millimeters and macroscopically visible in both, the Artik tuff and the concrete. In the natural stone, their abundance is slightly higher than in the ARB2 sample. During the production of the aggregate using the jaw crusher, a large part of the soft pumice clasts were probably broken and pulverized, so that the brown components in the concrete are only sporadically present. However, the visible pores of the pumice clasts in the tuff are visually well replaced by the large pores in the cement paste. Overall, the visual similarity can be rated as very satisfactory.

The yellowish to golden matrix of the Golden Armenia could be replicated very well with the cement paste. In this case, the matrix of the concrete is slightly darker and minimally greener than that of the aggregate. The latter is probably due to the original coloring of the gray cement. The Golden Armenia concrete shows significantly larger pores, in contrast to the Golden Armenia tuff, which exhibits significantly more pumice clasts. Nevertheless, a visually very well matching Golden Armenia has been developed (Fig. 19B).

The reproduction of the porous holocrystalline fabric of the Sissian basalt is difficult to realize with the standard cement used. Nevertheless, a good result has been achieved with regard to the coloring of the cement paste, since the basalt components in the concrete do not differ significantly in color from the base material (Fig. 19C). In comparison to the natural stone, it can be seen that the appearance of the concrete nevertheless differs slightly from this. This is due to the dark mafic to ultramafic inclusions, which occur less frequently in the concrete and the luster of the mica minerals. In addition, the highly porous content gives the basalt a darker appearance.

Deep black concrete surfaces with a coloration like that of the Gyumri Black tuff are difficult to realize in practice (Fig. 19D). Because of the formation of the cement needles...
during the hardening process, a diffuse light scattering on the surface will always occur, there is always a brightening of the concrete (Weber 2007). Taking these aspects into account, the coloration of the Gyumri concrete with 7 wt.% oxide black can be rated as very good (Fig. 19D). The cement paste is slightly lighter than the aggregate and can be described as dark anthracite. It should be noted that a very high pigment content can change the concrete properties and is associated with higher costs. With other pigments, e.g., carbon pigments, more extensive test series could be carried out to produce darker shades with the same pigment content.

The results show that the replication of the appearance of natural stones with cement paste tuffs, due to the very fine-grained cryptocrystalline to glassy matrix, can be better realized than for rocks with a holocrystalline matrix. In addition, the black concrete specimens, due to the change in color of the cement paste to lighter shades during setting, is more difficult to realize than lighter specimens.

For a comparative representation of the physical and technical properties of the natural stones and the optimized concrete specimens, an evaluation scheme has been created, so that the deviation of the concrete results from the parent rock can be divided into classes and is provided with a color code. The respective limit values are shown in Table 8. In Table 9, the scheme has been implemented and the results are compared.

### Pore space properties

According to the classification of Moos and Quervain (1948), the Artik and Golden Armenia can be described as rocks with a significantly high pore space. Gyumri Black and the Sissian Basalt are classified as rocks with many pores. The stones have high porosities and a high proportion of capillary pores.

In comparison to the source rocks, a high to very high agreement of the concrete specimens with respect to porosity and density values (Table 9) could be analyzed. A slightly increased deviation was found for the bulk density of GYB2, which differed by 0.17 g/cm³ from Gyumri Black. The mean pore radii determined by mercury porosimetry and the proportions of micropores and capillary pores of samples GYB2 and SIB3 differ significantly from the natural stones. For ARB2 and GAB2 the deviation is smaller and can be evaluated as moderate according to the established criteria. The investigated samples show an exponential decrease in the percentage of micropores with increasing mean pore radius. With exception of the Golden Armenia, the natural stones can be clearly distinguished from the concrete due to the

| Table 8 | Criteria for evaluating the suitability as a building stone and artificial replacement stones (concrete) in relation to selected parameters |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | high            | moderate        | low             |                |
| Porosity in %   | <20             | 20-40           | >40             |                |
| Micropores in % | <10             | 10-60           | >60             |                |
| Capillary pores in % | <30            | 30-80           | >80             |                |
| w-value in kg/m² | <3              | 3-20            | >20             |                |
| µ-value          | >12             | 8-12            | <8              |                |
| Hygric sorption in wt.% | <2             | 2-7             | >7              |                |
| Compressive strength in MPa | >40            | 30-40           | <30             |                |
| Flexural strength in MPa | >4             | 2-4             | <2              |                |
| Rebound hardness HCl | >600           | 400-600         | <400            |                |
| Ultrasonic velocity in km/s | >3             | 2-3             | <2              |                |
| Hydric expansion in mm/m | <0.25          | 0.25-0.5        | >0.5            |                |
| a in 10⁻⁸K⁻¹ | <6              | 6-9             | >9              |                |
| Residual strain in mm/m | <0.25          | 0.25-0.5        | >0.5            |                |
| Material loss in wt.% | <3             | 3-5             | >5              |                |

The coloring was done according to the criteria in Table 8

| Table 9 | Comparison of the petrophysical properties of the Armenia source rocks with the optimized concrete mixtures for artificial replacement stones |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sample ID       | Gyumri Black    | Artik Rosa      | Golden Armenia  | Sissian Basalt  |
| Porosity in %   | GYB2            | ARB2            | GA              | GAB2            | SI              | SIB3            |
| Bulk density in g/cm³ | 2.09            | 1.92            | 1.64            | 1.59            | 1.91            | 1.81            | 2.25            | 2.34            |
| Particle density in g/cm³ | 2.45            | 2.46            | 2.49            | 2.54            | 2.53            | 2.52            | 2.78            | 2.64            |
| Mean pore radius in pm | 1.75            | 0.68            | 1.77            | 0.38            | 0.48            | 0.08            | 2.37            | 0.04            |
| Micropores in % | 3.0             | 60.7            | 3.7             | 34.6            | 21.5            | 54.7            | 6.0             | 84.9            |
| Capillary pores in % | 97.0            | 31.3            | 96.3            | 65.4            | 78.5            | 43.3            | 94.0            | 15.1            |
| w-value in kg/m² | 4.3             | 1.8             | 6.6             | 2.0             | 4.5             | 2.0             | 1.3             | 1.0             |
| µ-value          | 24.2            | 33.1            | 12.6            | 15.0            | 14.5            | 17.6            | 18.8            | 52.2            |
| Hygric sorption in wt.% | 0.17            | 4.04            | 0.43            | 4.28            | 1.34            | 5.09            | 0.07            | 3.68            |
| Compressive strength in MPa | 78.2            | 54.2            | 41.6            | 38.9            | 60.5            | 46.7            | 67.6            | 61.1            |
| Flexural strength in MPa | 6.9             | 7.7             | 3.3             | 5.0             | 9.2             | 7.11            | 7.2             | 9.5             |
| Rebound hardness HCl | 691             | 60.2            | 490             | 487             | 546             | 500             | 536             | 621             |
| Ultrasonic velocity in km/s | 3.2             | 3.6             | 2.4             | 3.1             | 2.9             | 3.3             | 2.2             | 3.9             |
| Hydric expansion in mm/m | -0.06           | 0.49            | 0.06            | 0.45            | 0.49            | 0.82            | -0.01           | 0.61            |
| a in 10⁻⁸K⁻¹ | 7.0             | 8.3             | 5.3             | 7.3             | 4.6             | 8.0             | 2.4             | 8.3             |
| Residual strain in mm/m | 0.01            | 0.27            | -0.03           | 0.59            | 0.59            | 0.81            | -0.02           | 0.23            |
| Material loss in wt.% | <0.01           | 0.81            | <0.01           | 0.04            | 1.64            | 0.11            | <0.01           | <0.01           |

The coloring was done according to the criteria in Table 8
lower proportion of micropores and the larger pore radii. The results for the replacement stones indicate an increase in porosity with an increasing mean pore radius. The addition of air-entraining agents to the optimized mix formulas did not result in any increase in the mean pore radius, so that compared to the base rock these remain significantly lower in some cases. By means of the mercury porosimetry carried out the pore radius distribution could only be measured in the range of 1 nm and 100 µm. This measuring method is not suitable to detect larger capillary pores, air pores and compaction pores. Since in thin section the occurrence of these pores in the concrete samples and the Sissian basalt can be shown, it can be assumed that the actual mean pore radius could be significantly higher. Furthermore, the LP agent used has caused the formation of air voids in the cement paste, which can be detected by microscopic observation. When determining the effective porosity by means of buoyancy weighing, the large pores were also detected, so that the correlation between the porosity and the pore space properties obtained from mercury porosimetry may not be meaningful. In addition, the sometimes large difference in the mean pore radii between natural stone and concrete may be due to this.

Water transport

Many weathering processes of natural stone, such as frost and salt weathering as well as hydric and thermohydric strain, are controlled by the presence of water (Weiss et al. 2004; Siegesmund and Dürrast 2014; Pötzl et al. 2018). Therefore, the analysis of the water transport and water storage properties is essential to evaluate the durability of the construction material.

The most important processes of water transport in porous media are the water vapor diffusion and capillary water absorption (Siegesmund and Dürrast 2014). Both the porosity and the pore radius distribution have a major influence on the $\mu$ value, since in smaller pores at elevated air humidity, capillary condensation takes place (Krus 1995; Siegesmund and Dürrast 2014). This is also reflected in the results of the investigated natural stones and concrete samples. With the percentage of micropores, the $\mu$ value increases approximately linearly and decreases exponentially with increasing porosity. The capillary effect is the main driving force for water absorption through pores in the range between 1 µm and 1 mm. Accordingly, a high proportion of micropores reduces the capillary suction effect. The relationship between $w$ value and $\mu$ value can be described by an exponential function, since the capillary water absorption decreases with increasing water vapor diffusion resistance of the specimens, but this decrease quickly becomes smaller.

For the Sissian, Golden Armenia and Gyumri concretes, a high to very high agreement of the $w$ value could be achieved with respect to the natural stones (Table 9). Due to the stronger water absorption of the Artik Tuff, the standard deviation falls into the medium category. The $\mu$ values of GYB2, GAB2 and ARB2 correspond to those of the natural stones in a high to very high degree. Only the water vapor diffusion resistance of the sample SIB3 with 52.2 is clearly higher than that of the source rock.

The sorption results determined for the optimized concrete specimens show significantly higher values, which, according to the criteria in Table 8, all correspond to an average match to the parent rock. The extent of hygroscopic sorption is strongly determined by the specific internal surface area of a porous medium (Franzen and Mirwald 2004). Since this parameter was not determined for the concrete bodies, it can only be conjectured that the sorption values are higher due to this dependence. Pötzl et al. (2018) have shown on Armenian tufts that sorption at 95% r. h. tends to be greater for specimens with a higher micropore content. In addition, these tufts showed an increase in specific internal surface area with a higher content of micropores. As the concrete bodies have a very high content of micropores, it can, therefore, be assumed that the specific internal surface area is greater than in the natural stones and, due to this, the sorption values are significantly higher. The strong increase in weight of all the samples examined at high relative humidities can be attributed to the capillary condensation that takes place in the micropores (Krus 1995) and is accordingly less pronounced in the samples with a high capillary pore content.

The water retention capacity of natural stone and concrete varieties has not been quantified. However, based on the observation that the drying of the concrete specimens to mass constancy took considerably longer than that of the natural stones, it can be assumed that the retention potential of the hardened cement paste matrix is higher than for the source rocks.

Mechanical properties

The compressive strength of a building material is one of the most important mechanical properties. For concrete specimens, porosity has a decisive influence on strength (Stark and Wicht 2013). Other parameters, such as the water content or the age of a specimen, influences the compressive strength only as they modify the porosity and pore size distribution. In general, there is a dependence of the pore ratios in concrete on the $w/c$ value and the degree of hydration (Stark and Wicht 2013). A decrease of the $w/c$ value and an increasing degree of hydration entail a higher compressive strength, which is due to an increase in gel mass and a decrease in capillary pores (Stark and Wicht 2013).

The adjustment of the concrete formulas has resulted in a decrease in compressive strength for the Gyumri, Golden
Armenia and Sissian concretes. This can be explained by the addition of air-entraining agents, since the decrease in concrete strength is a negative side effect of air entrainment (Stark and Wicht 2013). However, LP agents also have a liquefying effect, so that the water demand is reduced, and no loss of strength occurs. For the second concrete formulas, the amount of water required for pre-saturation of the aggregate was decreased by increasing the superplasticizer content and adding the air-entraining agents. The compressive strengths of the three specimens were reduced, therefore, it can be assumed that the air-entraining agents were responsible for this. The increase in compressive strength of the second Artik concrete specimen can be presumably explained by the fact that the amount of water used to pre-saturate the aggregate was reduced the most among all the samples and had a higher effect on the compressive strength than the LP agent. The various hardness values of the concrete specimens can be explained by the linear dependency of these values with respect to the compressive strength.

The compressive strengths of ARB2 and SIB3 correspond to a high to very high degree with their source rocks (Table 9). For GYB2 and GAB2 a medium level of agreement could be achieved. In general, the compressive strength of the optimized concrete specimens is lower than that of the natural stones. This is mainly due to the strength class of the cement, the w/c ratio, and the pre-saturation of the aggregate. The higher the amount of water added to the pre-saturation, the lower the compressive strength, so that it can be assumed that the complete volume of liquid was not absorbed, and that the actual w/c ratio, therefore, increased. Since rebound hardness shows a linear relationship with compressive strength, the differences of both properties to the parent rock are comparable. For the flexural strength, a medium to high agreement could be achieved for the concrete specimens (Table 9). Except for GAB2, the values of the concrete exceed those of the parent rock. With regard to the ultrasonic velocities, with the exception of SIB3, good results were achieved in comparison with the natural stone.

**Weathering properties of tuffs and artificial replacement stones**

The evaluation of the durability of natural stones and concrete replacements used for buildings is of particular relevance, since, if this is not sufficiently given, considerable damage can occur. Investigations of the weathering properties of a building material are, therefore, indispensable. Therefore, the hydric and thermal expansion behavior as well as the resistance to freeze–thaw and de-icing salt of natural stones and the manufactured concrete samples have been investigated.

The hydric expansion of natural stones is considered to be one of the most important factors affecting the weathering influence (Wedekind et al. 2013). The reliable parameters for the estimation of the expansion behavior of tuffs are the proportion of the micropores, the hygroscopic sorption value, and the presence of swellable clay minerals (Pötzl et al. 2018). For the Sissian basalt as well as for the Artik Rosa and Gyumri Black tuffs, no significant hydric expansion was observed. Only the Golden Armenia shows a pronounced elongation behavior, which is related to the higher microporous content and the presence of the swellable clay mineral corrensite. In contrast to the natural stones, the concrete specimens all show a distinct hydric expansion, which is at least 0.45 mm/m. Based on the extremely high expansion of prepared water–cement samples, it can be concluded that the cement matrix is responsible for the difference between natural stone and concrete. Since the concrete has a high microporous content, it can be assumed that this is responsible for the hydric expansion. An exception are the GA concrete specimens, which show the strongest expansion behavior of all specimens. This is due to the aggregate, whose swellable clay minerals increase the expansion. Furthermore, a decrease in hydric strain with increasing w value has been identified. This correlation is due to the pore radii, as the samples with a high micropore content expand strongly, but show only a low capillary water absorption capacity and, in contrast, a high capillary pore fraction shows a high w value and a low hydric expansion.

Due to the stronger hydric expansion behavior, the match of GYB2 and SIB3 to the source rock is considered as moderate. For ARB2 and GAB2 the differences are smaller, so that the agreement was rated as high. Due to the stronger hydric expansion behavior, the agreement of GYB2 and SIB3 to the source rock is rated as medium. For ARB2 and GAB2 the differences are smaller, so that the agreement was rated as high.

Based on studies of Mexican tuffs by López-Doncel et al. (2018), three main factors have been identified that play an important role in the thermal expansion behavior of tuffs. These are the chemical composition, the proportion of crystals, and homogeneity in terms of fabric and microstructure. Generally, the coefficient of thermal expansion of rocks results from the α values of the minerals contained in them (Steiger et al. 2014). The thermal expansion of concrete depends primarily on the expansion coefficients of the cement paste and the aggregate. With typical α values between $1.1 \times 10^{-6} \text{ K}^{-1}$ and $20 \times 10^{-6} \text{ K}^{-1}$, the thermal expansion of the cement matrix is usually significantly higher than that of the aggregates (Neville 2011). This is also true for the concrete specimens, as the water–cement body has a larger $14.1 \times 10^{-6} \text{ K}^{-1}$ α value than the natural stones, which are in the range of $2.2 \times 10^{-6} \text{ K}^{-1}$ and $6.9 \times 10^{-6} \text{ K}^{-1}$. As expected, the concrete bodies have thermal expansion coefficients that range from $7.3 \times 10^{-6} \text{ K}^{-1}$ to $9.0 \times 10^{-6} \text{ K}^{-1}$ between the cement paste and the source rock. Steiger et al. (2014) show...
for different rock types, average thermal expansion coefficients in the range of $4 \times 10^{-6}$ K$^{-1}$ up to $12.5 \times 10^{-6}$ K$^{-1}$. Compared to the range of values, the coefficients of expansion of the natural stones investigated are considered to be low to moderate and those of the concrete specimens as moderate.

Any form of residual strain of a rock due to thermal stress contributes to decay (Siegesmund and Dürrast 2014). With the exception of the Golden Armenia, the natural stones show a negligible residual strain, both in the dry and wet condition. During the first dry cycle, the Golden Armenia shows negative residual strain, which presumably results from dehydration of the clay minerals present. The thermohydric stress, due to the flooding of the sample chamber, results in a strong residual strain of the Golden Armenia, which is caused by the hydric expansion due to the water addition. This is the result of the increased micropore content and the intra- and intercrystalline swelling of the clay minerals.

As the temperature increases, cement paste dehydrates continuously (Adam 2006). Zhang and Ye (2012) give a temperature of 105 °C for the onset of dehydration of the CSH (calcium silicate hydrate) phase of Portland cement. The thermal expansion curves of the concrete specimens show that at about 85 °C a shrinkage of all concrete drill cores takes place, resulting in an increasing negative residual strain. A possible reason for this could be that de-watering reactions in the cement paste already occur below 90 °C, which triggered the contraction of the specimens. The thermal loading of the concrete specimens in the wet state has a high residual strain and is the result of hydric expansion, due to the addition of the water in interaction with the thermal expansion.

Since the frost resistance of the natural stones can be considered as given on the basis of the freeze–thaw salt tests, the frost resistance of the concrete specimens is primarily a function of the properties of the pore structure of the cement matrix (Haist et al. 2009). The w/c ratio is considered as a central parameter for concrete to exhibit high resistance to freeze–thaw alternation (Haist et al. 2009). Although a low w/c ratio of 0.44 was used for the concrete production, the GAB1, ARB1, and GYB1 specimens showed excessive weathering as a result of freeze–thaw cycles. An explanation could be the amount of water added to the aggregate, which allowed a good workability of the concrete. Assuming that a higher amount of liquid was added than was necessary to saturate the natural stone aggregate, the actual w/c ratio increased during mixing of the formulas, the pore structure changed, and frost resistance was reduced. This is supported by the fact that the SIB1 cube, whose aggregate was not presaturated, showed the least weathering and was rated as frost resistant according to the evaluation criterion.

The addition of the LP agent to the optimized formulas increased the freeze–thaw resistance of the cement paste in all samples by the formation of air pores. Therefore, all the adjusted concrete varieties, with the exception of SIB2, can be considered frost resistant and meet the requirement of exposure class XF4. Furthermore, the amount of water used to pre-saturate the aggregate has been reduced, so that the actual w/c ratio has presumably decreased, which may have slightly increased the resistance. As already discussed for the pore space properties, the change in the proportion of air voids could not be determined by mercury porosimetry. Nevertheless, based on the Sissian concrete specimens SIB1 and SIB3, it can be concluded that the air-entraining agent has a decisive influence on the weathering resistance.

### Evaluation of the tuff and artificial replacement stone

To evaluate the natural stones and the concrete samples in terms of their suitability as replacement stones, a classification system has been applied, which is based on the examples of Visser and Mirwald (1998) and Kück (2019). Based on the defined threshold values, it is possible to classify the selected properties into the classes of high, moderate, or low suitability (Table 10). In Table 11, the assessment scheme has been implemented and the results are compared.

To quantify the suitability of the natural stones and concretes as artificial replacement stones, points have been assigned according to the classification of a property. For the category high 3 points, two points for moderate and one point for low suitability. Based on this point system, the natural stones achieved mean values per property between 2.4 (Golden Armenia) and 2.8 (Sissian). The mean values of the Artik Rosa and Gyumri Black are 2.5 and 2.7, respectively. Thus, the investigated natural stones can be considered as very suitable building materials.

The average suitability of the developed concrete samples is somewhat lower than that of the source rocks and is in the range of 2.3 (GAB2) and 2.6 (GYB2 and SIB3). ARB2 obtained a value of 2.4. Due to the fact that the natural stones have a very high suitability, and the concretes are only 0.1 to 0.2 points below, the result of the production of the developed concrete can be rated as very satisfactory. With regard to the properties considered, three of the four concrete varieties showed comparable or higher suitability as a building stone than the much used Golden Armenia. In the evaluation carried out, it should be noted that all parameters with respect to the influence of the properties on the suitability were assumed to be the same, and no weighting of the individual parameters was carried out. In addition, the criteria and their limit values were based on the prevailing environmental conditions and can differ from region to region in different parts of the world.
With regard to the pore radius distribution, the results of the concrete can be evaluated differently. The partly, very high proportion of micropores presumably caused the low $w$ values of the concretes, which is regarded as positive with respect to the use as a building stone. In contrast, the micropores in the cement matrix are probably responsible for the, compared to the natural stones, high hygroscopic sorption as well as the high hydric and thermohydric elongation, which are considered negative properties for the suitability as a construction material. The pore structure of the concrete specimens deviates significantly in its size distribution from that of the parent rocks. To produce a high capillary pore content in the cement paste, a high w/c ratio is required (Stark and wicht 2000, 2013; Haist et al. 2009). However, this causes an increase in frost sensitivity and a decrease in the strength of the concrete, so that its suitability as a building stone would decrease significantly. An increase in the capillary pore content while maintaining the same durability is, therefore, possible with the used Portland limestone cement and also the other types of cement used.

The hydric strain behavior of the concrete bodies as well as the pronounced residual strain due to the thermohydric loading cycles are to be evaluated as critical. They represent load-independent strain processes, which can cause irreversible changes in the shape of the concrete replacement stones, and thus induce stresses in the masonry. In addition, the concrete varieties show a significantly higher hygroscopic sorption compared to the source stone. It is, therefore, recommended that, if the concrete replacement stones are to be installed together with their source stones, that they be used in an environment with a moderate water load, to avoid stresses in the masonry due to the different expansion behavior between the concrete and the natural stones.

The freeze–thaw tests of the optimized specimens showed that the replacement stones will be able...
to withstand the winter climate with their numerous freeze–thaw cycles. The mechanical properties of the concretes can be rated as very good with regard to their suitability as building stones, since the compressive strength of the concretes is very good, the compressive strengths are in the moderate to high range, and the flexural strength exceeds that of the natural stones in some cases. Due to the double-shell construction of many historic buildings, the outer shell often has a non-load-bearing function, so that load-dependent damage to the facing masonry is not to be expected.

**Conclusions**

The development of stone replacement mortars using crushed rock as a base and different binder materials has been successfully demonstrated in this study. Water transport is a negative aspect with regard to the SRMs. Since this aspect is an important property especially in the context of facades exposed to water, modifications should be made to adjust these values. One possibility is to improve the grading curve and change the water content to improve the pore sizes or to use air-entraining agents. Another aspect is the irreversible residual strain, caused by thermal stress, which could lead to material loss within the weathering of the replacement mortar. Promising results, however, were obtained for most of the technical properties and these can be used for further optimizations.

The absence of larger clasts within the replacement mortars has been taken into account as the workability is an indispensable aspect. In comparison to the replacement stone, the final surface will always be produced manually and never with a saw or comparable equipment. Therefore, larger clasts will cause an unprocessable mortar.

The use of durable replacement stones, which are produced from the unusable waste from processed tuff rocks or overburden, can provide a resource-saving alternative for the restoration of buildings. Therefore, four natural stone imitations made of concrete have been developed, which can be used as potential artificial stones in the course of restoration work. The investigations showed that these stones have a porosity with a high capillary pore content and show strong water absorption. The selected natural stones show a high suitability for use as a building stone. They have relatively high strengths, hydric and thermohydric expansion behavior is in some cases very low, and all samples show a high frost resistance. Thus, the requirements for the respective replacement stones achieved a very good match to the natural stone and as a suitable construction material substitute. Based on the results of the first concrete mixtures, it was necessary to adjust some components. Corrections have been made to the pigment and superplasticizer contents to optimize the cement paste coloration and reduce the amount of water added to pre-saturate the aggregate. In addition, air-entraining agents have been used as the tuff concretes did not show sufficient resistance during the freeze–thaw cycles.

The optimization of the concrete mixtures resulted in an improved macroscopic appearance, a reduced thermal expansion behavior and a very high frost resistance. However, a slight decrease in the compressive strength results. Comparing of the data of the natural stones with the optimized concrete specimens showed that, on average, a medium to high agreement of the properties was achieved. Tuffs are more suitable for replication as compared to the Sissian basalt investigated. The basalt shows the highest differences compared to the respective natural stone. Both the natural stones and the developed concrete varieties, according to the established criteria, have a good suitability as an ashlar. Due to certain water transport and weathering properties of the concrete specimens, it is recommended that they should be installed in parts of buildings which are not exposed to constant water saturation.

Whenever the suitability of a replacement mortar or replacement stone needs to be evaluated, the specific environmental and exposure conditions must always be taken into account. Therefore, an environmental analysis of the conditions is necessary to understand what requirements the rock replacement material must meet. In addition, a resource-saving approach was pursued by recycling waste material. This is particularly important, as sustainability and the effective use of raw materials are playing an increasingly important role in our society. Nevertheless, it remains to be noted that the pore structure of the cement paste differs from the matrix of the natural stones. In a continuation of this work, further test series could be carried out and the use of alternative binders as well as further additives and admixtures could be tested to further increase the conformity of the concrete replacement to the natural stone.

With regard to the quality requirements, each stone replacement mortar should meet the requirements of the source stone and deviate between 50 and 100% with regard to the technical properties (Snethlage and Pfanner 2020). It has been shown in this study that it is possible to produce stone replacement mortars for selected rock varieties (e.g., volcanic tuff stones), and to adjust the color by adding pigments. The comparison of the optical appearance of the developed SRM to the respective source rocks is very important for evaluating the success of the developed mixture. The original appearance of the structure should not be affected by the installation of the stone replacement and the visual difference between the different building materials should be minimal. In some cases, it is even intended that different repair phases should be visually recognizable.
Visual appearance

Aesthetic requirements for the use of black replacement materials in buildings or monuments range from graded anthracite colorations to blue–black shades (Zimmer 2015). Deep black concrete surfaces with a color scheme like that of the Gyumri Black tuff are difficult to realize in practice. Since the formation of cement needles during the setting process results in diffuse light scattering on the surface, there is always a lightening of the concrete (Weber 2007). A very high pigment content would have a negative effect on the concrete properties and also increase the costs. More extensive test series could be carried out with colorants, such as carbon pigments, to produce darker shades with the same pigment content.

The yellowish to golden matrix of the Golden Armenia could be reproduced very well with the cement paste. In this case, the base mass of the concrete is slightly darker and minimally greener than that of the aggregate. The latter is probably due to the original coloration of the gray cement. Since the Golden Armenia, unlike the Artik Rosa, does not have pumice clasts with large pores, the concrete has significantly more macroscopically visible large pores. Nevertheless, an artificial stone visually very well adapted to the Golden Armenia has been developed.

The color coding of the porous holocrystalline fabric of the Sissian basalt is difficult to realize with the cement available on the market and is difficult to achieve. However, a good result has been achieved with regard to the coloration of the cement paste, since the basalt components in the replacement materials do not differ significantly in color from the base compound. Compared to the natural stone, it can be seen that the appearance of the concrete is nevertheless slightly different from it. This is due to the dark mafic to ultramafic inclusions, which occur less frequently in concrete, and the luster of the mica minerals. In addition, the presence of a highly porous fabric gives the basalt a darker appearance.

Basically, a very good color match was achieved by creating a systematic color series. The use of white cements facilitates color matching, since other binders may have a specific inherent color and thus significantly influence color optimization. Taking into account the natural stone tuff, it should be emphasized that clast and component parts in the original stone support a color and decor deviation.

Technical properties and sustainability

A very important property is the strength characteristics. Sufficient formability is achieved by adjusting the Young’s modulus. It is advisable that the replacement materials have a lower modulus of elasticity, < 80% of the initial aggregate, so that masonry stresses can be absorbed to prevent cracking. Due to the stresses to be expected at the interfaces between the SRM or the artificial replacement stone with the original rock, a reduction of the strength even below 60% is recommended. These strengths can be easily achieved with the binders we use. In addition, modified stone admixture formulations lead to a decrease in compressive strength by adding air-entraining agents or by increasing the water–cement ratio, among other things. Only systematic test series will result in an optimized problem solution here.

To avoid stresses, the thermal and moisture expansion of the stone replacement materials should be as small as possible. Our systematic findings of thermal and thermohygric strain show that all replacement materials can exhibit significantly higher residual strain amounts compared to the respective source rock. Overall, the residual strain amounts of all the developed replacement materials are to be evaluated more critically, since, among other things, differences to the source rock could be shown. Here, temperature is a critical parameter, as the replacement materials in particular react very sensitively at high temperatures. Therefore, with regard to practical applications, it must be questioned whether the replacement materials really have to withstand such a high load. Both the expansion and shrinkage behavior of the mortar under the influence of temperature and moisture should be matched as closely as possible to the original stone. The better the adaptation of the additives to the original rock, the lower the stresses that occur at the interfaces. The associated losses in terms of durability can lead to detachment of the mortar. For a quality check, the α-coefficients are compared with each other. The mortar should be in the range of 50–150% in thermal and thermohygic strain, with respect to the original stone. As the α-expansion coefficients are compared in the quality test, it can be seen that all the replacement materials meet the requirements. Nevertheless, for a critical evaluation, the residual strain amounts due to thermal loads should be taken into account.

From a preservation perspective, the replacement materials generally should have a higher porosity than the original rock, so that water transport and drying processes tend to take place in the mortar rather than in the rock itself. As an example, the rule of thumb is almost always achieved for sandstones, since, on the one hand, they only have a porosity above 30% in individual cases and, on the other hand, a mortar produced by hand achieves a porosity above 30%. However, this does not apply to tuffs, which have a very wide porosity spectrum. Snethlage and Pfanner (2020) limit the requirements of the w value between 50% and 100%. For the water vapor diffusion, the SRM should also be between 50% and 100% of the original rock. Both water absorption and water vapor diffusion ensure a moisture balance between mortar and stone and are decisive for the durability of the applied replacement materials. Air entraining agents can play an important role here, provided one manages to create pores of certain pore classes.

Long-term durability can best be performed on sample bodies or sample surfaces by weathering simulations on
composite specimens for freeze–thaw resistance, salt crystallization test, and thermo-hygic strain behavior.

Using different binder mixtures, both advantages and disadvantages of the developed stone replacement materials could be demonstrated. Based on this, further optimization is possible and, in the best case, leads to application in practice. Another positive aspect is that SRM production is not dependent on the use of newly mined rock material. Conversely, this means that declared waste material from the natural stone industry can serve as the basis for SRMs. With regard to the sustainability of resource materials, the economic and ecological aspects have thus been taken into account. However, it is still considered a disadvantage that a whole series of experiments must be carried out for the implementation of such SRMs to achieve an appropriate fit. In addition, financial resources, and the capacities for such a project must be available, justifying, among other things, more elaborate test series. This is especially true in the case of high-ranking and historically significant cultural assets, such as the Hercules Monument in Kassel, Germany (UNESCO World Heritage site).

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Declarations

Conflict of interest The authors declare that there are no conflict of interest.

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