



# Assessment of Rock Aggregate Quality Through the Analytic Hierarchy Process (AHP)

Ekin Köken · Soner Top · Ahmet Özarslan

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**Abstract** The present study aimed to assess rock aggregate quality through the Analytic Hierarchy Process (AHP). In the context of the AHP analyses, four rock types (i.e., andesite, basalt, granodiorite, and gabbro), five evaluation criteria, and several technical requirements/suggestions for coarse aggregates related to bituminous paving mixtures were considered. In order to set over the evaluation criteria, detailed laboratory studies were conducted. For this purpose, various mineralogical, physical, and mechanical aggregate properties were determined for each rock type concerning their weathering grades. As a result of the laboratory studies, it was determined that the rock weathering processes have substantial negative impacts on the rock aggregate properties considered in this study. The AHP analysis results indicated that that different rock types have several advantages concerning various evaluation criteria. Based on the general evaluation point (EP) of the rocks, the gabbros were found to have the highest rock aggregate quality (EP = 0.393). In contrast, the andesites had

the lowest quality (EP = 0.069). Besides, the basalts (EP = 0.271) and granodiorites (EP = 0.267) presented approximately the same quality for their use in bituminous pavement mixtures. It was also demonstrated that the AHP, with its specific methodology, can be utilized to represent different environmental and mechanical conditions by changing the relative weight of the evaluation criteria. In this way, the pros and cons of different rock types could be revealed quantitatively, which enables related engineers to select proper rock types for their use under different environmental and mechanical conditions. From this point of view, the present study could be declared a case study noted for combining theoretical and practical approaches on bituminous paving mixtures as a sign of rock aggregate quality.

**Keywords** Analytic hierarchy process · Crushed stone · Aggregate quality assessment · Rock weathering

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E. Köken (✉) · S. Top  
Materials Science and Nanotechnology Engineering  
Department, Abdullah Gül University, 38010 Kayseri,  
Turkey  
e-mail: ekin.koken@agu.edu.tr

A. Özarslan  
Mining Engineering Department, Zonguldak Bülent  
Ecevit University, 67100 Zonguldak, Turkey

## 1 Introduction

Aggregates are granular geomaterials composed of crushed rocks on a large scale. They are the world's leading construction and building resources concerning both tonnage and economic value. Addressing,

serviceability, and long-term durability of rock aggregates are the issues that have a direct link to their quality. In this context, crushed rocks with different size fractions have been utilized regarding their material properties such as strength, hardness, and abrasion resistance within certain limits designated by various organizations/institutions.

Researchers have attempted to analyze the quality of rock aggregates, whether they are suitable for related engineering applications (Al-Harhi 2001; Khanal and Tamrakar 2009; Langer 2016). Rock aggregates with high-quality have higher strength and durability properties compared to those with low-quality (Kencanawati et al. 2017; Kalra and Mehmood 2018). Thanks to the high quality of rock aggregates, they provide engineers with reducing dead loads of structures through lower cross-sections available (Beshr et al. 2003).

Moreover, high-quality rock aggregates or their recycled derivatives have been investigated for concrete and bituminous paving mixtures from many aspects (Akbulut et al. 2011; Brand et al. 2015; Beushausen and Dittmer 2015; Omary et al. 2016; Šernas et al. 2016; Herndon et al. 2016; Yang and Lee 2017; Thomas et al. 2018; Choorackal et al. 2019).

The resistance of aggregates against mechanical impacts and environmental conditions vary greatly depending upon several variables such as their strength, lithological variances, textural, and mineralogical features. As for lithological differences of rocks, certain rock types such as gabbro, basalt, rhyolite, limestone, and quartzite were reported as suitable natural resources for the production of high-quality rock aggregates (Langer 2001; Smith and Collis 2001). Parallel to this statement, Carrión et al. (2014) stated that limestones and basalts with high-quality could be considered when dealing with the production of concrete sleepers, which are one of the essential elements in railway track infrastructures.

Apart from the initial suitability of rock aggregates, their ongoing performance under various environmental, static and dynamic loading conditions is associated with the mineralogical and petrographical features (Kimiya 1982; Azzoni et al. 1996; Irfan 1999; Smith and Collis 2001; Zorlu et al. 2008).

Therefore, the weathering degree of rocks becomes prominent. Rock weathering is a disintegration process of rocks arising from dramatic changes in the physical, chemical, and biological environments.

Scientific approaches aiming to reveal and quantify rock weathering could provide knowledge about the quality of rock aggregates in general. The lack of this knowledge causes overestimations, and hence anticipated performance and serviceability of rocks could be interrupted. By investigating rock weathering processes, the efficiency and sustainability of rock quarrying could be improved throughout the rock quarrying (Irfan 1994; Rigopoulos et al. 2012; Köken 2019).

Qualitative and quantitative approaches have been adopted to reveal the weathering degree of rocks in a wide variety of rock engineering applications. The qualitative methods are mainly based on geological and geotechnical field observations such as variations in color, texture, and structural features of rock masses related to discontinuities, bedding planes, etc. (Beavis 1985; Bell 2007). On the other hand, several physico-mechanical properties (i.e., apparent porosity  $n_c$  (%), dry density ( $\rho_d$ ,  $g/cm^3$ ), point load strength (PLS, MPa), uniaxial compressive strength (UCS, MPa), pulse wave velocity ( $V_p$ , km/s)) have also been considered for investigating the weathering effects on various rock materials (Irfan and Dearman 1978a; Karpuz and Paşamehmetoglu 1997; Tugrul and Zarif 2000; Ceryan et al. 2008; Marques et al. 2010; Momeni et al. 2015; Koca and Kınca 2016; Köken et al. 2016; Ündül and Tugrul 2016; Köken and Özarslan 2018; Koca and Koca 2019).

Furthermore, several researchers examined the effects of rock weathering from textural and mineralogical points of view. For instance, Irfan and Dearman (1978b) proposed a micro-petrographical index ( $I_p$ ) for the evaluation of rock weathering for granitic rocks. Tuğrul (1995) proposed a quantitative approach based on measuring micro-crack lengths observed in thin sections within specified areas. This quantitative approach was referred to as micro-fracture density ( $q_{mf}$ ,  $mm/mm^2$ ) and determined by the following equation:

$$q_{mf} = L/A_c \quad (1)$$

where:  $L$  is the total length of micro-fractures (mm) in a specified area of  $1 \text{ mm}^2$  ( $A_c = 1 \text{ mm}^2$ ).

Rock weathering in view of mineralogical variances or impurities was also explored by loss on ignition (LOI, %) tests that presented relatively easier results for the evaluation of rock weathering (Arıkan

et al. 2007; Ündül and Tuğrul 2012; Koca and Kınal 2016; Köken and Özarslan 2018). In rock quarries, rock aggregates are conventionally produced through several series of drilling–blasting and crushing–screening operations. Drilling–blasting operations in/on rock masses are mainly performed as if the related rock mass is made up of a single structural unit, that is, various weathering zones in/on rock masses are occasionally overlooked. However, it is not a realistic approach. Rock masses have actually lateral and vertical transitions that separate them into different structural units in terms of weathering degrees (Fig. 1). These structural units are sometimes easy to separable by the naked eye, whereas some of them could be very complex.

Due to the coexistence of rock masses with different weathering grades, rock aggregates as a product could probably include weathered particles. This phenomenon, therefore, will undoubtedly affect the quality of rock aggregates in total. Even though crushed rock blocks with different weathering grades are attempted to be separated by crushing–screening operations, weathered rock aggregates with different size fractions could inevitably be found in the desired product.

Although the adverse effects of weathering processes on rock material and rock mass properties have been documented widely (e.g., Karpuz and Paşamehmetoglu 1997; Jaboyedoff et al. 2004; Tuğrul 2004; Arıkan et al. 2007; Gokceoglu et al. 2009; Akın

2010; Marques et al. 2010; Koca and Kınal 2016; Gürocak and Yalcin 2016), apart from several tentative inferences, there is quite limited information on how weathering processes affect the rock aggregate quality.

Herein, the main objective of the present study is to introduce an Analytic Hierarchy Process (AHP) for the assessment of rock aggregate quality in terms of bituminous paving mixtures. For this purpose, four different rock masses located in different parts of Turkey were considered. The rock masses were characterized and divided into different structural zones in terms of weathering grades (i.e., unweathered ( $W_0$ ), slightly weathered ( $W_1$ ), moderately weathered ( $W_2$ ), and highly weathered ( $W_3$ )). Based on the laboratory test results of several mineralogical, physical, and mechanical aggregate properties, the quality of rock aggregates was evaluated through the AHP. As a consequence of the AHP analyses, the quality of the investigated rock types was compared with one another, considering various evaluation criteria.

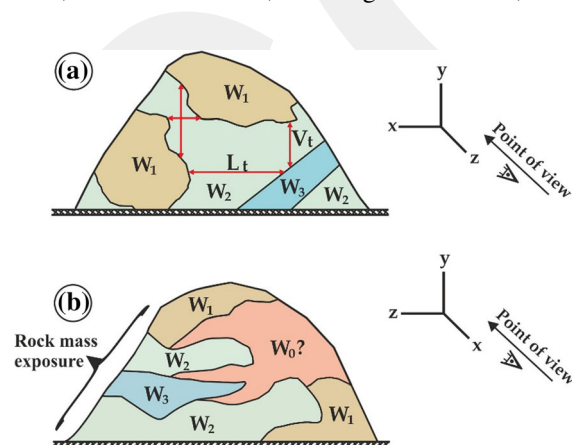
## 2 Materials and Methods

### 2.1 Materials

Four different rock masses located in different parts of Turkey were investigated and characterized by field observations. The rock masses considered are igneous in origin, and their geological features are summarized in Table 1. During field observations, each rock mass was divided into four different structural zones based on their weathering grades ( $W_0$ – $W_3$ ), where a qualitative approach suggested by the International Society of Rock Mechanics (ISRM 2007) was adopted. Representative rock blocks with different weathering grades were obtained for laboratory studies (Fig. 2).

In practical applications, the andesitic rocks have been mainly regarded as coping and dimension stone that has no load-bearing capability (Erdoğan et al. 2012; Kun 2013), whereas the basaltic rocks have been mainly used as stone dust/wool, surface treatment, concrete, and railway ballast aggregate (Aydın 2015; Doğruöz et al. 2016; Köken and Özarslan 2016; Bayhan and Bağcı 2018; Köken 2019).

On the other hand, the granodioritic rocks have been used as coping/dimension stone, and surface treatment aggregate in stabilized and bituminous roads



**Fig. 1** Schematic illustration of a rock mass with different weathering grades **a** Vertical cross-section **b** Longitudinal cross-section ( $W_0$ : Unweathered,  $W_1$ : Slightly weathered,  $W_2$ : Moderately weathered,  $W_3$ : Highly weathered,  $L_t$ : Lateral transition distance,  $V_t$ : Vertical transition distance, Note: Schematic illustration is not to scale)

**Table 1** Geological features of the rock masses investigated

Rock type	Location	Geological setting	
		Group/formation	Geological age
(a) Andesite	Havran/Balıkesir	Kızılkıran formation <sup>I</sup>	Oligocene–Miocene <sup>I</sup>
(b) Basalt	Işıkkara/Kütahya	Karacaören volcanites <sup>II</sup>	Miocene–Pliocene <sup>II</sup>
(c) Granodiorite	Havran/Balıkesir	Çamlık granitoids <sup>III</sup>	Devonian <sup>III</sup>
(d) Gabbro	Kayadibi/Karabük	Bolu granitoid complex <sup>IV</sup>	Pre-Cambrian <sup>IV</sup>

References I: Krushensky et al. (1980), II: Demirbilek (2005), III: Okay et al. (1996), IV: Erendil et al. (1991)

in various parts of western Turkey (Erdoğan et al. 2012). The gabbroic rocks located in and around Karabük region have been used as surface treatment, concrete and railway ballast aggregate in local railway routes located in the Blacksea region (Keserci 2014; Arıoğlu 2015; Köken 2019).

## 2.2 Methods

Laboratory studies were divided into two different parts. In the first part, mineralogical features of rock materials were determined for each weathering grade. Mineralogical characterizations were carried out by thin section observations and X-ray diffraction (XRD) analyses. For each rock type, thin sections were prepared, and they were analyzed under a polarized microscope. The XRD analyses were performed by a Bruker Discover D8 diffractometer, analyzing grinded rock samples with a particle size range of  $\sim 0.106$  mm.

Following the first part of the laboratory studies, rock aggregate properties such as water absorption by weight ( $w_a$ , %), specific gravity ( $G_s$ ), Los Angeles abrasion loss (LAA, %), magnesium sulfate weight loss ( $M_{wl}$ , %) and the brittleness index ( $S_{20}$ , %) were determined for each rock type concerning their weathering grades. The  $w_a$  and  $G_s$  of rock aggregates were determined, considering BS EN 1097-6 (2013). The LAA and  $M_{wl}$  tests were performed in accordance with BS EN 1097-2 (2010) and BS EN 1367-2 (2009), respectively. The  $S_{20}$  was also determined considering the methodologies of Dahl et al. (2012).

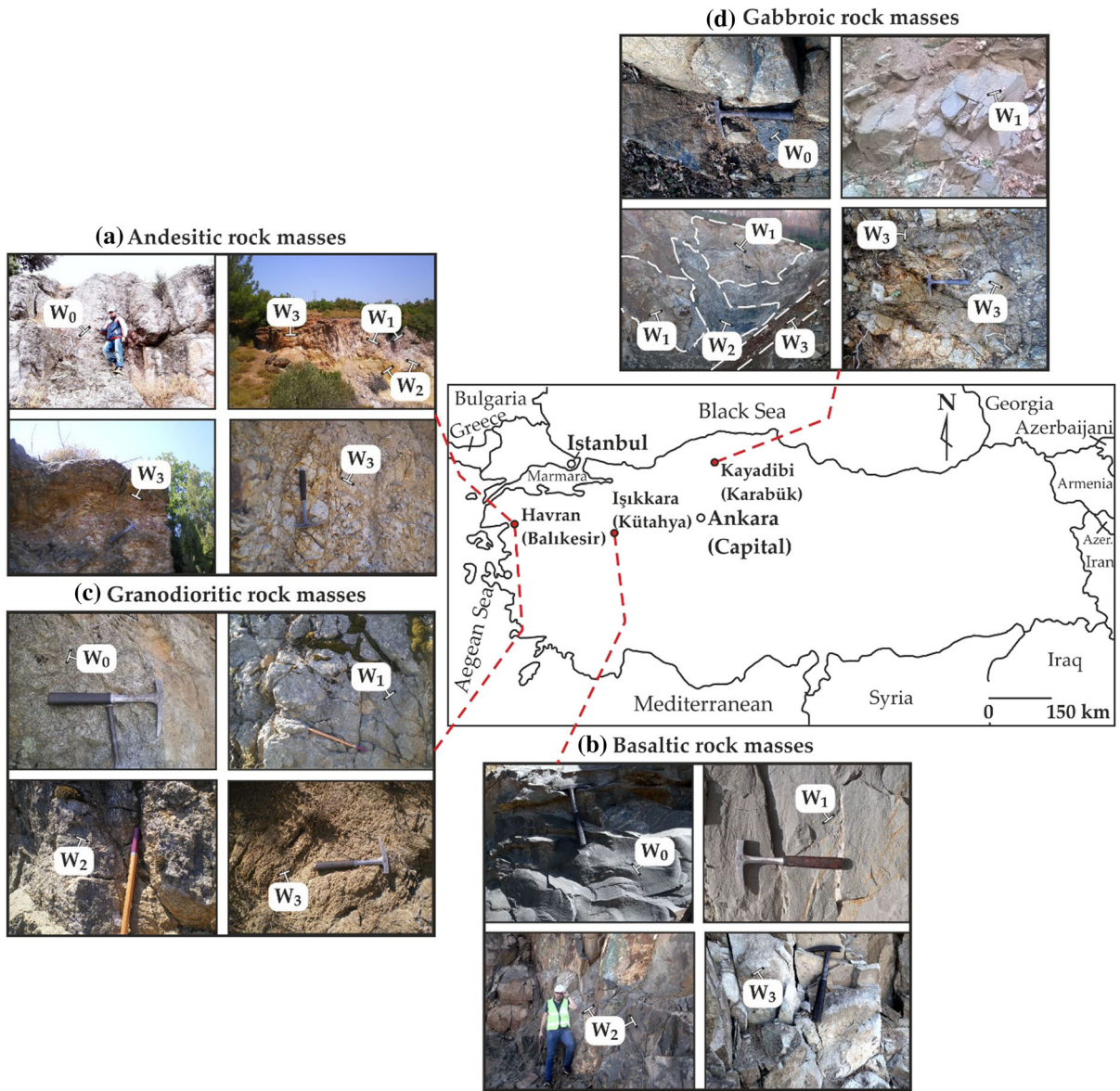
### 2.2.1 Mineralogical and Textural Analyses

The determination and quantification of rock-forming minerals were performed by two different methods. In

the first method, thin sections were prepared and analyzed under a polarized microscope, where the point-counting method was adopted to quantify the rock-forming minerals. In the second method, XRD analyses were performed, and the patterns were analyzed using the Panalytical Highscore Plus software with a mineral database of PDF<sup>2</sup>. The results obtained from the mentioned methods were evaluated together so that the mineralogical compositions of rock materials were determined for each weathering grade. Typical thin sections and XRD patterns of the rock materials with different weathering grades are given in Fig. 3.

### 2.2.2 Loss on Ignition Tests, Micro-fracture Density, and Micro-petrographical Index Measurements

The effects of rock weathering on the aggregate quality were also investigated by loss on ignition (LOI, %) tests that were carried out in accordance with ASTM D7348 (2013). The LOI tests were repeated ten times, and average values were presented. The  $q_{mf}$  measurements were performed using thin sections, measuring micro-crack lengths occupied in a specified area ( $A_c = 1$  mm<sup>2</sup>). Several image analysis techniques (i.e., scaling, separation, and filtering), some parts of which were partially adopted from Arena et al. (2014), were drawn on to observe the persistency of micro-cracks. During image analysis processes, vertical and horizontal cross-sections were established. A total of 30 measurements (in two equal parts considering horizontal and vertical cross-sections) were carried out for each rock sample, and the  $q_{mf}$  values were determined by Eq. 1.



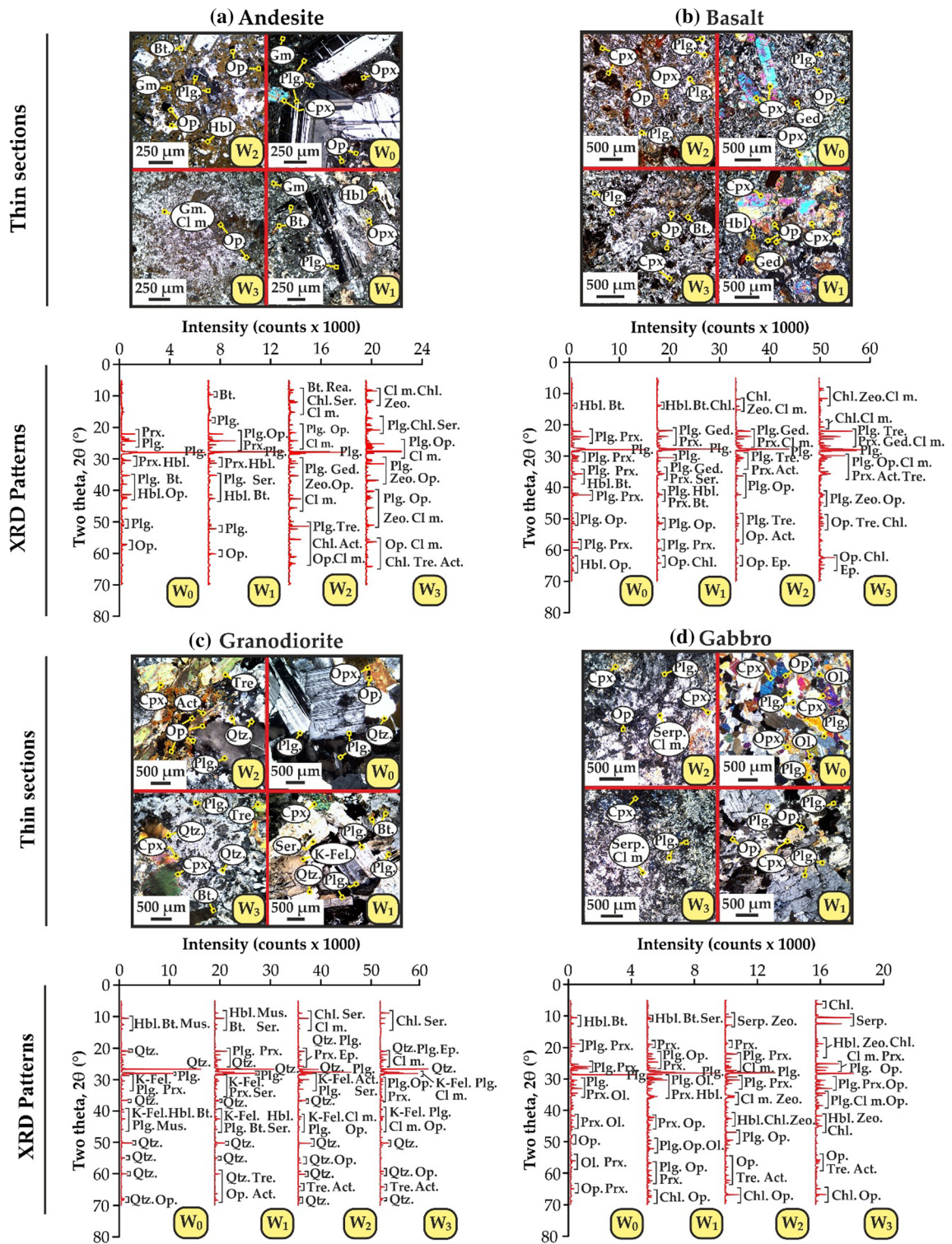
**Fig. 2** Sampling locating map for the rock masses considered in this study (W<sub>0</sub>: Unweathered, W<sub>1</sub>: Slightly weathered, W<sub>2</sub>: Moderately weathered, W<sub>3</sub>: Highly weathered)

### 2.2.3 Water Absorption and Specific Gravity Tests

The determinations of  $w_a$  and  $G_s$  were carried out using rock aggregates with a particle size range of 11.2–16 mm. The tests were carried out in accordance with BS EN 1097-6 (2013). Each test was repeated ten times, and the average values were presented.

### 2.2.4 Los Angeles Abrasion Tests

The LAA tests were performed in accordance with BS EN 1097-2 (2010). For this purpose, rock aggregates with a particle size range of 11.2–16 mm were prepared. The LAA tests were repeated three times for each rock type concerning their weathering grade, and the average values were presented.



**Fig. 3** Thin sections and XRD patterns of the investigated rocks **a** Andesite **b** Basalt **c** Granodiorite **d** Gabbro (Qtz: Quartz, Plg: Plagioclase, K-Fel: Alkali Feldspar, Cpx: Clino-pyroxene, Opx: Ortho-pyroxene, Ol: Olivine, Hbl: Hornblende, Tre: Tremolite, Act:

Actinolite, Chl: Chlorite, Ep: Epidote, Ser: Sericite, Bt: Biotite, Mus: Muscovite, Ged: Gedrite, Op: Opaque minerals, Cl m: Clay group minerals Serp: Serpentine group minerals, Zeo: Zeolite group minerals)

### 2.2.5 Magnesium Sulfate Soundness Tests

Magnesium sulfate soundness is a kind of accelerated weathering test that simulates natural freezing–thawing effects (Wu et al. 1998; Jayawickrama et al. 2007; Ioannou et al. 2013). The tests were conducted in accordance with BS EN 1367-2 (2009).

Rock aggregates with a particle size range of 10–14 mm were prepared, and a total of  $500 \pm 10$  g oven-dried rock aggregates were placed in a saturated magnesium sulfate solution for 16–18 h at room temperature ( $18 \pm 2$  °C). Following the immersion of rock aggregates, they were taken out of the solution and left to drain for 4–6 h. Then, pre-treated rock aggregates were placed in a drying oven at  $105 \pm 2$  °C for 24 h. The whole process described herein was identified as one cycle of magnesium sulfate soundness test, and the process was repeated for five times. After five cycles of magnesium sulfate soundness tests, the  $M_{w1}$  was determined based on the total weight loss in rock aggregates with reference to a 10.0 mm sieve.

### 2.2.6 The $S_{20}$ Brittleness Index Test

The  $S_{20}$  brittleness index test is suitable for the aggregates with a particle size range of 11.2–16.0 mm. The test provides knowledge about the resistance of rock aggregates against repeated impact loads. The  $S_{20}$  brittleness index tests were carried out according to the methodologies described by Dahl et al. (2012). For each rock type, the brittleness tests were repeated five times, and the average values were presented.

## 3 Analytic Hierarchy Process (AHP)

The AHP is a user-friendly engineering tool when dealing with the decision-making processes of complex problems (Ishizaka and Labib 2009). The AHP is carried out, dividing problems into hierarchical structures that could be made up of both countable and uncountable variables (Saaty 2008). A typical hierarchical structure in AHP analyses is composed of three main components, such as alternatives, criteria, and a goal. In this study, the AHP analyses were performed specifically for the evaluation of coarse rock aggregates, which could be used in bituminous pavement mixtures.

The evaluation criteria for the AHP analyses are listed in Table 2. In the AHP analyses, four rock types and five evaluation criteria were established (Fig. 4). The analyses were performed regarding the variations in physical, mechanical, and mineralogical features of rock aggregates due to the rock weathering, weatherability trends of the rocks, and the technical standards of ASTM D962/962M (2015). Since there is not a definite TLV for  $w_a$  in ASTM D962/962M (2015), the practical experiences on coarse aggregates used in bituminous paving mixtures were considered.

Based on the international experiences on bituminous paving mixtures, the TLV for  $w_a$  could be declared as  $\leq 2\%$  (Rajagopal and Crago 2007; Al-sansary and Iyengar 2013; Iskender et al. 2016; Tahmoorian et al. 2017). Moreover, several findings, suggestions, or supportive data for the suitability of coarse aggregates were also integrated into the construction of some evaluation criteria (e.g., the criterion of  $C_3$  and  $C_5$ ).

Based on a comparison matrix of A (Eq. 2), each criterion ( $C_1$ – $C_5$ ) was quantified by the following matrix system;

$$A = \begin{bmatrix} 1 & a_1/a_2 & a_1/a_3 & a_1/a_n \\ a_2/a_1 & 1 & a_2/a_3 & a_2/a_n \\ a_3/a_1 & a_3/a_2 & 1 & a_3/a_n \\ a_n/a_1 & a_n/a_2 & a_n/a_3 & 1 \end{bmatrix} \quad (2)$$

where  $a_1$  is the weight of the first element, and  $a_n$  is the weight of the  $n_{th}$  element.

Comparison matrices were constructed for each criterion, combining the related TLVs, selected rock properties corresponding to the  $W_0$  weathering type ( $V_{(w_0)}$ ), and the weatherability trend of the rocks.

As a consequence of these combinations, a rating point (RP) was calculated for each rock type by the following equation;

$$RP_{(\max - \min)} = \ln \left( \frac{TLV}{V_{(w_0)} \times t_1} \right) \times \frac{1}{t_2} \quad (3)$$

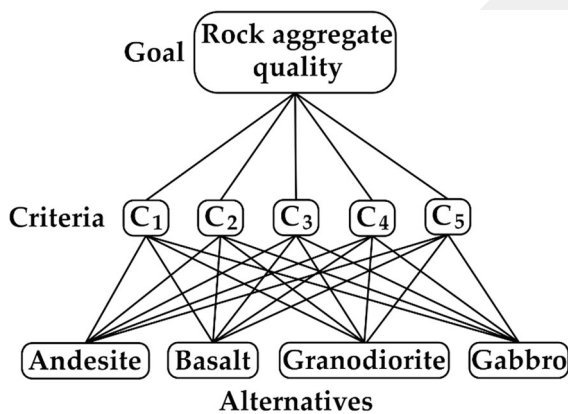
where  $t_1$  and  $t_2$  are the constants for different rock types based on their weatherability trends. The TLV is the threshold limit value considered in the analyses (Table 2), and the  $V_{(w_0)}$  is the individual rock aggregate property corresponding to the  $W_0$  type of rock.

After the determination of the RPs, the transformation of them into Saaty’s 9-point scale (Comparison

**Table 2** Fundamental criteria adopted in the AHP analyses

Evaluation criterion	Identification	Variable considered	Standard/ methodology	Threshold limit value (TLV)
C <sub>1</sub>	Tendency to disintegration against simulated freezing–thawing cycles	M <sub>wl</sub> (%)	ASTM C88/C88M (2018) BS EN 1367–2 (2009)	M <sub>wl</sub> ≤ 18% (ASTM D692/D692M 2015)
C <sub>2</sub>	Tendency to disintegration against abrasion and fragmentation	LAA (%)	ASTM C131/C131M (2020) BS EN 1097–2 (2010)	LAA ≤ 40% (ASTM D692/D692M 2015)
C <sub>3</sub>	Tendency to disintegration against repeated impact loads	S <sub>20</sub> (%)	Dahl et al. (2012)	S <sub>20</sub> ≤ 45% (modified after Dahl et al. 2012; Köken et al. 2018)
C <sub>4</sub>	Water absorption susceptibility	w <sub>a</sub> (%)	BS EN 1097–6 (2013)	w <sub>a</sub> ≤ 2% (Tahmoorian et al. 2017)
C <sub>5</sub>	Mineralogical suitability	q <sub>m</sub> f (mm/mm <sup>2</sup> )	Thin section observations	q <sub>m</sub> f ≤ 1 mm/mm <sup>2</sup> (Proposed in this study)

For the criterion of C<sub>1</sub>–C<sub>2</sub>, the BS EN norms were adopted

**Fig. 4** AHP structure adopted in this study

Point, CP) was performed by correlating these values (i.e., RPs and CPs). These correlations were carried out considering Table 3, where the minimum and maximum RPs should be 1 and 9, respectively. The RPs between those were determined by exponential interpolations of the CPs. A typical comparison matrix and an illustration of such transformations are given in Fig. 5.

In Fig. 5, different RPs calculated from Eq. 3 are plotted separately for the rocks investigated. Based on the assumption that the rock with the highest RP for the criterion C<sub>4</sub> has the highest relative interest (e.g., the RP is 6.739 for gabbro). In other words, the

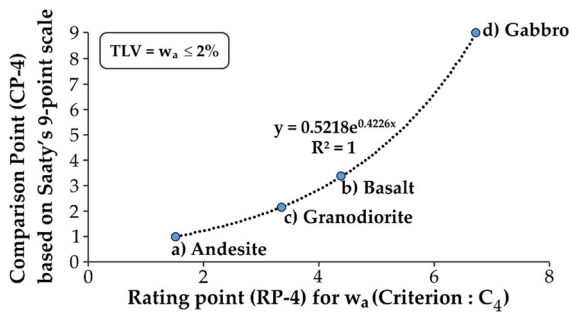
**Table 3** Saaty's 9-point rating scale (modified after Saaty 2008)

Importance level	Comparison point (CP)
Equal	1
Weak or slightly considerable	2
Moderate	3–4
Strong	5–6
Very Strong	7–8
Extreme	9

rock with the highest RP gets the highest CP (CP = 9).

Similarly, the ones with the lowest RP (e.g., the RP is 1.540 for andesite) get the lowest CP. (CP = 1) in Fig. 5. For the other rock types concerning their aggregate properties, the RPs were calculated and adapted to the Saaty's 9-point rating scale (Table 3), considering their significance level. Different interpolation techniques (i.e., linear, logarithmic, etc.) were also explored for the adaption of RPs and CPs, and it was determined that the exponential interpolation gave more reasonable results and provided a much better statistical significance.

In the light of the above-mentioned explanations, initial comparison matrices were constructed and solved for each criterion until the analyses were



Basic comparison matrix of the C <sub>4</sub>					a) Andesite	b) Basalt
C <sub>4</sub>	a	b	c	d	V <sub>w<sub>a</sub></sub> (W <sub>0</sub> ) = 1.55%	V <sub>w<sub>a</sub></sub> (W <sub>0</sub> ) = 0.32%
a	1.00	0.30	0.46	0.11	t <sub>1</sub> = 0.555	t <sub>1</sub> = 0.437
b	3.36	1.00	2.19	0.37	t <sub>2</sub> = 0.548	t <sub>2</sub> = 0.604
c	2.17	0.46	1.00	0.24		
d	9.00	2.68	4.14	1.00		
Total	15.53	4.44	7.79	1.73		
Transformed comparison matrix of the C <sub>4</sub>					c) Granodiorite	d) Gabbro
C <sub>4</sub>	a	b	c	d	V <sub>w<sub>a</sub></sub> (W <sub>0</sub> ) = 0.34%	V <sub>w<sub>a</sub></sub> (W <sub>0</sub> ) = 0.11%
a	0.06	0.07	0.06	0.06	t <sub>1</sub> = 0.473	t <sub>1</sub> = 0.554
b	0.22	0.23	0.28	0.22	t <sub>2</sub> = 0.747	t <sub>2</sub> = 0.518
c	0.14	0.10	0.13	0.14		
d	0.58	0.60	0.53	0.58		
Total	1.00	1.00	1.00	1.00		

**Fig. 5** Illustration of typical comparison matrix and transformation of RPs to Saaty’s 9-point scale

verified statistically. The statistical verification of the AHP analyses was performed, determining the Consistency Index (CI) and the Consistency Ratio (CR). The CI and CR (Saaty 2008) was calculated by the following equations;

$$CI = \frac{(\lambda_{max} - n_s)}{(n_s - 1)} \tag{4}$$

where  $\lambda_{max}$  is the maximum eigenvalue of the comparison matrix of A and  $n_s$  is the size of the matrix (for this study,  $n_s = 4$ ).

$$CR = \frac{CI}{RI} \tag{5}$$

where RI represents Saaty’s random consistency index (Table 4) based on the size of the comparison matrix A.

If the CR is less than or equal to 0.10, the AHP analysis could be declared admissible (Saaty 2008). Otherwise, the comparison matrix should be revised, and the analysis requires repetition with new comparison matrices. Following the methodology described herein, the AHP analyses were performed using the software MATLAB R2019a.

**Table 4** Saaty’s random consistency indices (Saaty 1980)

Matrix size (n <sub>s</sub> )	Random consistency index (RI)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41

## 4 Results and Discussion

### 4.1 Effects of Rock Weathering on The Mineralogical and Textural Features

Thin section analyses showed that the textures of rock materials change substantially with progressive rock weathering. Based on thin-section observations and XRD analysis results, mineralogical compositions of rock materials are listed in Table 5.

It was determined that the quantity of several rock-forming minerals decreases with progressive weathering, which could be attributed to various mineral alternations. For instance, it is clear that with progressive rock weathering, the quantities of Plg. minerals altered to Cl m. and Zeo. minerals in andesites and basalts.

For granodiorites, Mus. and Bt. minerals altered to Ser. minerals, beginning from W<sub>1</sub> type of rock weathering. The Prx. minerals such as Augite and Diopside altered to Tre., Act., and Op. minerals in such cases. The quantity of Ol. and Prx. minerals decreased with progressive rock weathering that clarifies the increase in Serp. minerals for gabbroic rocks. Other mineralogical variances due to rock weathering could be seen in Table 5.

The mineralogical variations of q<sub>mf</sub> and LOI due to rock weathering are listed in Table 6. Accordingly, the q<sub>mf</sub> values increased remarkably in parallel with progressive rock weathering. The remarkable changes in the q<sub>mf</sub> values were typical, especially beginning from the W<sub>2</sub> type of rock weathering for all rock types. The increase in q<sub>mf</sub> values could be interpreted as increasing release surface areas, decreasing the

**Table 5** Mineralogical composition of the investigated rocks with different grades

Minerals	(a) Andesite				(b) Basalt				(c) Granodiorite				(d) Gabbro			
	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>
Plagioclase (Plg) <sup>(1)</sup>	56	52	44	38	47	49	45	39	32	34	35	33	64	62	51	34
Biotite (Bt)	7	3	2	–	6	5	1	–	6	4	1	–	3	4	–	–
Muscovite	–	1	–	–	1	1	1	–	4	2	–	–	–	–	–	–
Hornblende (Hbl)	6	8	1	–	8	5	1	–	3	4	2	3	5	6	6	8
Gedrite (Ged)	–	1	3	1	1	4	6	4	–	–	–	–	–	–	–	–
Epidote (Ep)	1	1	–	–	1	1	–	–	–	1	2	2	1	1	2	1
Opaque minerals (Op) <sup>(2)</sup>	5	6	9	11	6	6	8	6	6	4	3	4	6	5	8	11
Pyroxene (Cpx + Opx)	2	1	–	–	12	10	6	4	8	7	5	3	16	14	9	3
Quartz (Qtz)	–	–	–	–	–	–	–	–	29	27	28	26	–	–	–	–
K-Feldspar (K-Fel) <sup>(3)</sup>	–	–	–	–	–	–	–	–	12	8	6	6	–	–	–	–
Chlorite (Chl)	–	–	6	4	–	1	2	5	–	1	7	3	–	2	5	6
Olivine (Ol)	–	–	–	–	1	–	–	–	–	–	–	–	5	3	1	–
Serpentine (Serp) <sup>(4)</sup>	–	–	–	–	–	–	–	–	–	–	–	–	–	–	4	15
Cinnabar (Cin)	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Realgar (Rea)	–	–	2	1	–	–	–	–	–	–	–	–	–	–	–	–
Zeolite (Zeo) <sup>(5)</sup>	–	–	1	4	–	–	2	6	–	–	–	–	–	–	3	5
Sericite (Ser)	–	3	2	1	–	–	1	–	–	3	1	2	–	3	1	–
Tremolite (Tre)	–	–	1	2	–	–	2	5	–	2	2	5	–	–	2	3
Actinolite (Act)	–	–	1	1	–	–	2	–	–	2	2	1	–	–	3	6
Anthophyllite (Anth)	–	–	–	–	–	–	1	1	–	–	1	1	–	–	–	–
Clay minerals (Cl m.) <sup>(6)</sup>	–	–	6	12	–	1	6	9	–	1	5	11	–	–	5	8
Ground mass (Gm) <sup>(7)</sup>	23	24	21	25	17	17	16	21	–	–	–	–	–	–	–	–

*Explanations* (1): Plagioclase minerals: Albite (Na-rich)–Anorthite (Ca-rich) series with different quantities. (2): Opaque minerals: Magnetite, Hematite, Goethite, Rutile, Ilmenite, Cordierite, Garnet, (3): K-Fel: Orthoclase and Microcline. (4): Serpentine group minerals: Antigorite, Lizardite. (5): Zeolite group minerals: Amicite, Boggsite, Ferrierite. (6): Clay minerals: Illite, Sepiolite, Smectite, Kaolinite, Montmorillonite. (7): Groundmass: Not crystallized associations observed in thin sections (i.e., for andesitic and basaltic rocks, the quantities of groundmass were quantified by correlating values of thin section observations and XRD analysis results). W<sub>0</sub>: Unweathered, W<sub>1</sub>: Slightly weathered, W<sub>2</sub>: Moderately weathered, W<sub>3</sub>: Highly weathered

stiffness of rock and tendency to water–rock interactions (Arıkan et al. 2007).

Increasing the LOI values seen in Table 6 could also give a relative measure representing the adverse effects rock weathering on rock aggregate quality from a mineralogical point of view. Similar trends in LOI values due to progressive rock weathering were also reported by Irfan (1994), Arıkan et al. (2007), Ceryan (2008), Regassa et al. (2014), Ündül and Tugrul (2016) and Köken and Özarslan (2018).

Moreover, the increase in the Chl., Cl m. and Zeo. minerals could give a rapid estimation for the assessment of weathering degree in the investigated rocks. From mineralogical points of view, it was determined

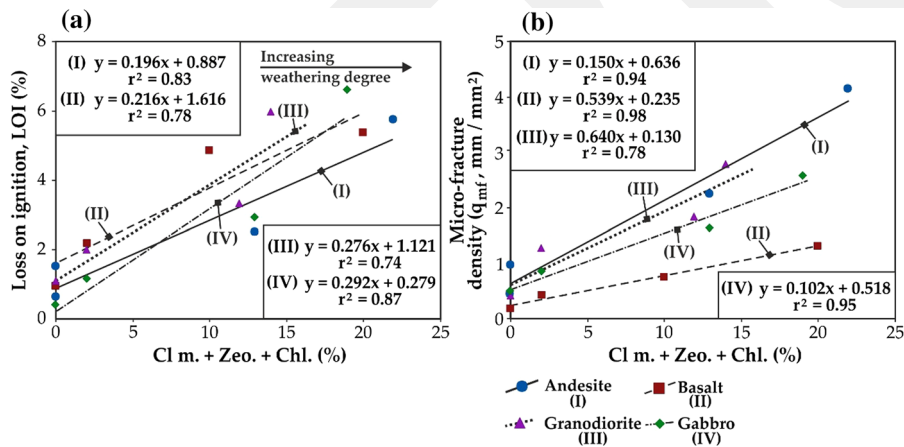
that the sum of these minerals increased remarkably with progressive rock weathering for all rock types, which has similarities with the findings of Ceryan (2008). Focusing on this phenomenon, remarkable relationships were also obtained between those of mineralogical variances,  $q_{mf}$ , and the LOI (Fig. 6).

Moreover, the serpentinization in ultramafic rocks, such as dunites and ophiolitic melanges, is another indicator of rock weathering that shows decreasing its strength properties (Giannakopoulou et al. 2018). From the W<sub>2</sub> type of rock weathering, serpentinization was obvious for the gabbroic rocks (Table 5), which could be a key point for the evaluation of degradation

**Table 6** The variations in  $q_{mf}$  and LOI values arising from progressive rock weathering

Rock type	Weathering degree	$q_{mf}$ (mm/mm <sup>2</sup> )	LOI (%)
(a) Andesite	W <sub>0</sub>	0.44	0.64
	W <sub>1</sub>	0.97	1.52
	W <sub>2</sub>	2.25	2.49
	W <sub>3</sub>	4.14	5.76
(b) Basalt	W <sub>0</sub>	0.18	0.95
	W <sub>1</sub>	0.42	2.19
	W <sub>2</sub>	0.75	4.86
	W <sub>3</sub>	1.32	5.39
(c) Granodiorite	W <sub>0</sub>	0.40	1.04
	W <sub>1</sub>	1.25	1.96
	W <sub>2</sub>	1.80	3.28
	W <sub>3</sub>	2.77	5.94
(d) Gabbro	W <sub>0</sub>	0.47	0.40
	W <sub>1</sub>	0.85	1.14
	W <sub>2</sub>	1.63	2.91
	W <sub>3</sub>	2.58	6.60

*Explanations*  $q_{mf}$ : Micro-fracture density, LOI: Loss on ignition (%), W<sub>0</sub>: Unweathered, W<sub>1</sub>: Slightly weathered, W<sub>2</sub>: Moderately weathered, W<sub>3</sub>: Highly weathered



**Fig. 6** Relationships showing the effects of rock weathering on several mineralogical features **a** LOI **b**  $q_{mf}$

potential and serviceability duration of them in different engineering purposes.

Briefly, rock weathering could be quantified and assessed, focusing on the mineralogical variables of Chl., Cl m. and Zeo. minerals for the investigated rocks. The more these minerals are present, the higher degree of weathering the investigated rocks could have. The variations in  $q_{mf}$  and LOI values could also be declared as beneficial parameters that could be reliably considered for rock weathering and quality assessments.

#### 4.2 Effects of Rock Weathering on the Aggregate Properties

Based on the laboratory studies, physical and mechanical rock aggregate properties are listed in Table 7. Comparing the aggregate properties of W<sub>0</sub> types with those of W<sub>3</sub> types, the rate of decrease (ROD, %) in the G<sub>s</sub> values ranged between 7 and 9% for all rock types. The rate of increase (ROI, %) in the  $w_a$ ,  $M_{wl}$ , the S<sub>20</sub>, and LAA values were found to be in the ranges of 370–830%, 384–965%, 44–84% and 62–130%, respectively.

**Table 7** Variations in rock aggregate properties arising from progressive rock weathering

	(a) Andesite Weathering degree					(b) Basalt Weathering degree			
	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>		W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>
G <sub>s</sub>	2.51	2.47	2.37	2.29	G <sub>s</sub>	2.77	2.71	2.67	2.54
M <sub>wl</sub> (%)	5.66	8.57	15.16	27.44	M <sub>wl</sub> (%)	1.17	1.82	4.04	11.75
LAA (%)	30.39	34.74	45.56	49.30	LAA (%)	14.31	19.94	25.41	32.80
S <sub>20</sub> (%)	37.70	46.08	56.32	65.90	S <sub>20</sub> (%)	40.74	48.19	53.48	59.16
w <sub>a</sub> (%)	1.55	2.63	3.82	8.53	w <sub>a</sub> (%)	0.32	0.37	0.71	1.93

	(c) Granodiorite Weathering degree					(d) Gabbro Weathering degree			
	W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>		W <sub>0</sub>	W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>
G <sub>s</sub>	2.83	2.74	2.68	2.62	G <sub>s</sub>	2.91	2.85	2.75	2.69
M <sub>wl</sub> (%)	0.74	1.51	2.47	6.60	M <sub>wl</sub> (%)	0.83	1.40	3.71	8.84
LAA (%)	20.26	23.41	27.66	29.83	LAA (%)	12.07	16.54	19.45	26.51
S <sub>20</sub> (%)	33.26	37.25	44.09	58.15	S <sub>20</sub> (%)	25.41	36.57	39.23	46.58
w <sub>a</sub> (%)	0.34	0.71	1.55	3.17	w <sub>a</sub> (%)	0.11	0.16	0.27	0.52

*Explanations* G<sub>s</sub>: Specific gravity, M<sub>wl</sub>: Magnesium sulfate soundness, S<sub>20</sub>: The brittleness index, w<sub>a</sub>: Water absorption by weight, LAA: Los Angeles abrasion value, W<sub>0</sub>: Unweathered, W<sub>1</sub>: Slightly weathered, W<sub>2</sub>: Moderately weathered, W<sub>3</sub>: Highly weathered

Based on the above-mentioned variations, it could be claimed that rock aggregate properties of w<sub>a</sub> and M<sub>wl</sub> seem to be more prone to progressive rock weathering rather than the other rock aggregate properties considered. However, it should be noted that these findings are only valid for the rocks investigated, and therefore, the number of samples should be increased to get generalized inferences.

From the W<sub>0</sub> to W<sub>3</sub> types of weathering degrees, the ROD in G<sub>s</sub> was reported at average rates of 1%, 4%, and 6% for quartzite, basalt, and granites, respectively (Gupta and Rao 1998). However, Tuğrul and Zarif (2000) and Arel and Tuğrul (2001) found no remarkable changes in the G<sub>s</sub> arising from rock weathering for limestones and granodiorites, respectively. The most substantial changes in the G<sub>s</sub> (for the above-mentioned comparison, the ROD ≈ 18%) arising from rock weathering was reported for dunites (Ündül and Tuğrul 2012). Apart from the G<sub>s</sub>, the variations in w<sub>a</sub> arising from rock weathering were focused more deeply in several previous studies (Fig. 7).

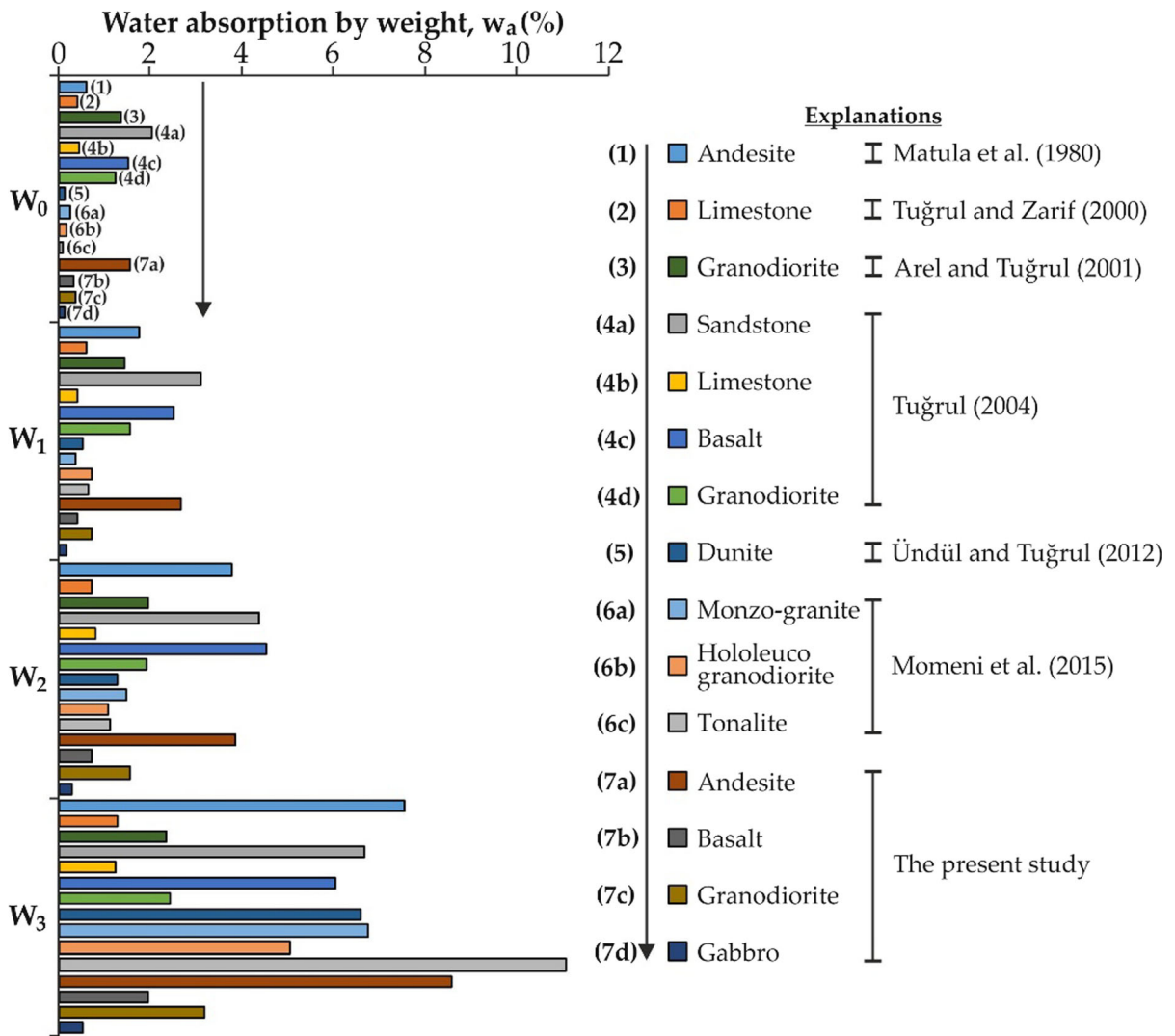
Accordingly, the increase in w<sub>a</sub> due to rock weathering is obvious, and therefore, the w<sub>a</sub> should be considered for both evaluating rock weathering degree and rock aggregate quality. The w<sub>a</sub>, in this direction, is not only an important variable for assessing rock weathering and rock aggregate quality but also could be a key parameter for determining asphalt absorption of rock aggregates in bituminous paving mixtures (Lee 1990; Tarrer and Wagh 1991).

When reconsidering the previous studies, it was observed that the effects of rock weathering on mechanical aggregate properties such as LAA and S<sub>20</sub> were not mentioned. In this respect, the laboratory test results in Table 7 provide a piece of knowledge on how the LAA and S<sub>20</sub> vary with progressive rock weathering for various rock types.

As for the M<sub>wl</sub> tests, since progressive rock weathering lets the pore size and geometry be enlarged in the rock itself (Tuğrul 2004), the drainage of magnesium sulfate solution into rocks is expected to be much easier in weathered rocks. Furthermore, progressive rock weathering also leads to generating additional micro-fissures in rocks. These two phenomena (enlargement of pore size and geometry and increase in micro-fissures) could be hence attributed to the substantial increase in the M<sub>wl</sub> values observed in the investigated rocks with W<sub>2</sub> and W<sub>3</sub> types. The considerable increase in the M<sub>wl</sub> due to rock weathering was also detected for granites located in southwest England (Irfan and Dearman 1978a).

#### 4.3 Weatherability Trends Based on Various Rock Aggregate Properties

The weatherability trends of the investigated rocks were revealed, focusing on the laboratory test results in Tables 6 and 7. Compared to the aggregate properties corresponding to the W<sub>0</sub> type with those with weathered ones (W<sub>1</sub>–W<sub>3</sub>), it was determined that



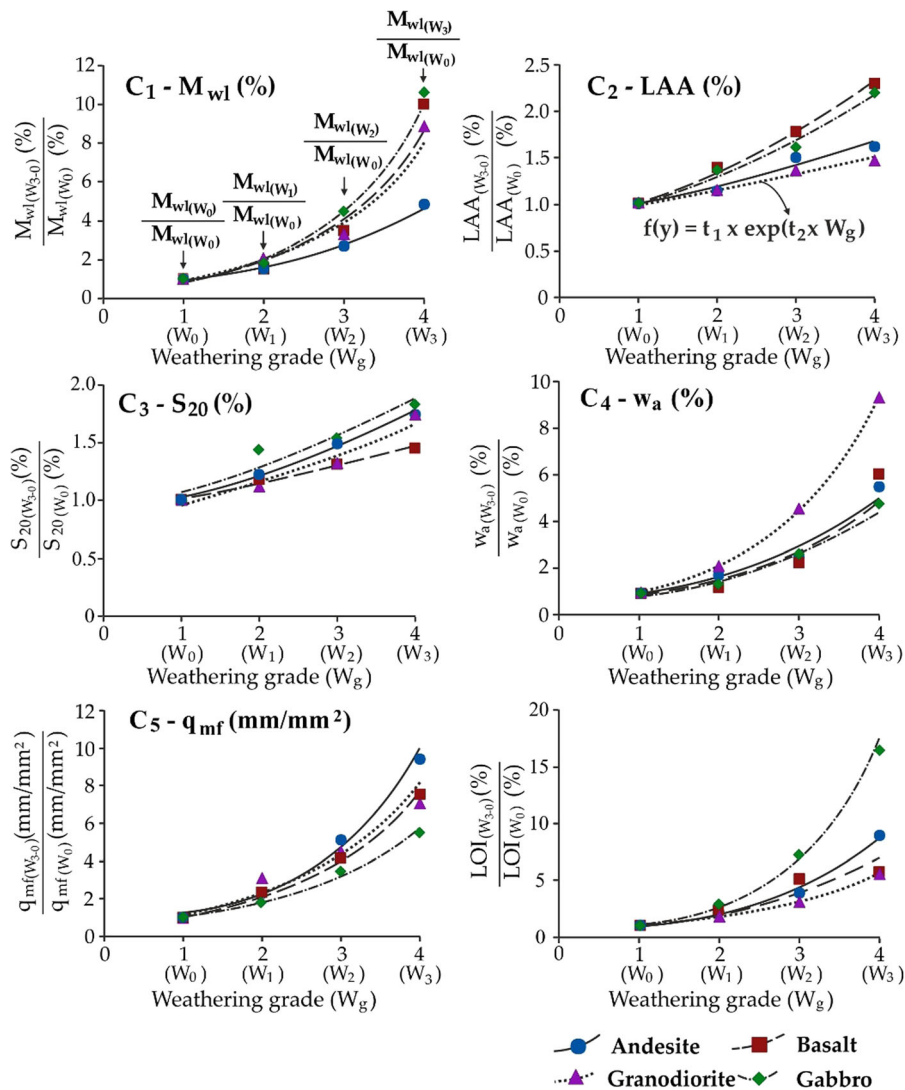
**Fig. 7** Variations in  $w_a$  of various rock types due to progressive rock weathering ( $W_0$ : Unweathered,  $W_1$ : Slightly weathered,  $W_2$ : Moderately weathered,  $W_3$ : Highly weathered)

the weatherability trends of the rocks increase exponentially with progressive rock weathering in different proportions (Fig. 8).

As a result of the correlations in Fig. 8, the weatherability trends in rocks were quantified as two constants (i.e.,  $t_1$  and  $t_2$ ), where higher  $t_2$  values mainly refer to a higher degree of susceptibility of rock aggregate properties to progressive rock weathering (Table 8).

For instance, with regards to the variations in  $M_{w1}$  and LOI values, gabbroic rocks seemed to have a higher susceptibility rather than other rock types. At the same time, the gabbros were found to have better

rock aggregate properties than those of the others. When considering the variations in  $w_a$  values, the granodiorites presented a higher weatherability trend for the criterion of  $C_4$ . Similar weatherability trends for  $w_a$  could also be obtained, considering the variations given in Fig. 7 for other rock types. In consequence of weatherability trend quantifications for each evaluation criterion ( $C_1$ – $C_5$ ), all input parameters for the AHP analyses were compiled.



**Fig. 8** Weatherability trends of the rocks based on various aggregate properties

**Table 8** Constants of  $t_1$  and  $t_2$  with reference to the evaluation criteria

Criteria	C <sub>1</sub>		C <sub>2</sub>		C <sub>3</sub>		Criteria	C <sub>4</sub>		C <sub>5</sub>	
Variable	M <sub>wl</sub> (%)		LAA (%)		S <sub>20</sub> (%)		Variable	w <sub>a</sub> (%)		q <sub>mf</sub> (mm/mm <sup>2</sup> )	
Constants	t <sub>1</sub>	t <sub>2</sub>	t <sub>1</sub>	t <sub>2</sub>	t <sub>1</sub>	t <sub>2</sub>	Constants	t <sub>1</sub>	t <sub>2</sub>	t <sub>1</sub>	t <sub>2</sub>
(a) Andesite	0.558	0.53	0.839	0.172	0.836	0.187	(a) Andesite	0.555	0.548	0.484	0.756
(b) Basalt	0.393	0.771	0.779	0.273	0.902	0.122	(b) Basalt	0.437	0.604	0.564	0.665
(c) Granodiorite	0.478	0.705	0.885	0.137	0.8	0.184	(c) Granodiorite	0.473	0.747	0.671	0.617
(d) Gabbro	0.398	0.807	0.789	0.252	0.886	0.188	(d) Gabbro	0.554	0.518	0.574	0.576

*Explanations* M<sub>wl</sub>: Magnesium sulfate soundness, LAA: Los Angeles abrasion value, S<sub>20</sub>: The brittleness index, w<sub>a</sub>: Water absorption by weight, q<sub>mf</sub>: Micro-fracture density

#### 4.4 Evaluation of Rock Aggregate Quality Through the AHP Analyses

The AHP analysis results are given in Table 9. Accordingly, the higher values obtained from the AHP analyses, the higher quality has the rock aggregate. For the criterion of C<sub>1</sub>, granodiorites presented the highest rock aggregate quality. Due to the presence of mafic minerals with relatively greater grain sizes than those of the other rock types, the gabbros seemed to be more prone to degradation against simulated freezing–thawing cycles than the granodiorites. For the criterion of C<sub>2</sub>, the granodiorites and gabbros provided approximately the same quality, but with a minute difference, the granodiorites took the lead. For other criteria, such as C<sub>3</sub>–C<sub>4</sub>, the gabbros became much prominent. According to the criterion of C<sub>5</sub>, the andesites presented the lowest aggregate quality owing to the steep increase in micro-fracture densities due to progressive rock weathering.

On the other hand, the basaltic rocks with fine-grained aphanitic texture yielded the prominence in terms of the criterion of C<sub>5</sub>. Contrary to seemingly having the highest mineralogical suitability, the basaltic rocks seemed to have a lower rock aggregate quality together with the andesites based on the criterion of C<sub>3</sub>. The granodiorites had a better rock aggregate quality than the basalts in terms of the C<sub>1</sub>–C<sub>3</sub> criteria.

Briefly, the rocks investigated with respect to rock aggregate quality could be sorted viably in the direction of the established criteria. Based on the general evaluation points (EP), the gabbros (EP = 0.393) were found to have the highest rock aggregate

quality, whereas the andesites (EP = 0.069) presented the lowest quality in general. In addition, the basalts (EP = 0.271) and the granodiorites (EP = 0.267) could be declared as presenting somewhat the same rock aggregate quality for their use in bituminous paving mixtures (Table 10).

It should be herein mentioned that the general evaluation of the investigated rocks (Table 10) is based on the assumption that each criterion acts equally (Case I in Fig. 9) on their overall quality. Should different relative weights of the evaluation criteria be considered, this gradation would be changeable. To represent different mechanical and environmental conditions to which the rocks could probably be exposed, the weights of the evaluation criteria were changed intentionally. As seen in Fig. 9, the gradation of the investigated rocks in terms of their overall quality changes with changing the relative weights of the evaluation criteria.

The remarkable changes in these gradations could be attributed to the fact that the assessment of rock aggregate quality is a tough issue. Regarding only the rock aggregate properties seems not to be sufficient. A comprehensive rock aggregate quality assessment could only be performed, considering rock aggregate properties, their weatherability trends, and the environmental and mechanical conditions to which the rocks will be exposed. In this way, the pros and cons of the investigated rocks could be revealed successfully under different environmental and mechanical conditions, where the AHP analyses could be highly beneficial.

With the AHP analyses, theoretical and practical approaches are gathered successfully. The AHP analyses consider fundamental rock aggregate properties

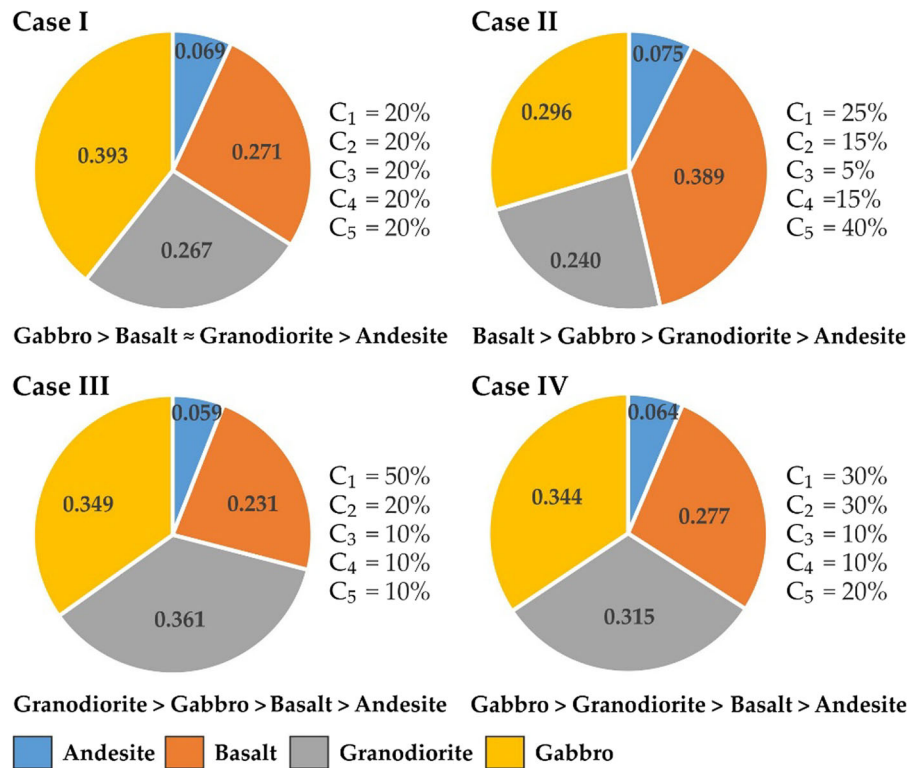
**Table 9** AHP analysis results

Rock type	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>5</sub>
(a) Andesite	0.052	0.044	0.079	0.064	0.104
(b) Basalt	0.197	0.166	0.066	0.235	<b>0.692</b>
(c) Granodiorite	<b>0.468</b>	<b>0.399</b>	0.264	0.128	0.077
(d) Gabbro	0.283	0.391	<b>0.592</b>	<b>0.574</b>	0.127
λ <sub>max</sub>	4.0155	4.0147	4.0158	4.0142	4.0150
CI	0.052	0.0049	0.0053	0.0047	0.0050
CR	0.0057	0.0054	0.0059	0.0053	0.0056

Note Bolded values (e.g., **0.592**) indicate the rock type with the highest aggregate quality concerning the evaluation criteria

**Table 10** Rock aggregate quality evaluation based on the AHP analyses

Criterion	Rock aggregate quality
C <sub>1</sub>	Granodiorite > Gabbro > Basalt > Andesite
C <sub>2</sub>	Granodiorite ≈ Gabbro > Basalt > Andesite
C <sub>3</sub>	Gabbro > Granodiorite > Andesite > Basalt
C <sub>4</sub>	Gabbro > Basalt > Granodiorite > Andesite
C <sub>5</sub>	Basalt > Gabbro > Granodiorite > Andesite
General	Gabbro > Basalt ≈ Granodiorite > Andesite
EP	0.393      0.271      0.267      0.069



**Fig. 9** Rock aggregate quality assessment concerning different relative weights of the evaluation criteria

together with mineralogical features of rocks, technical requirements and/or suggestions and the weatherability trends of rocks. Employing this comprehensive approach, the investigated rock types could be compared with one another based on different quantitative evaluation criteria for their use in bituminous paving mixtures.

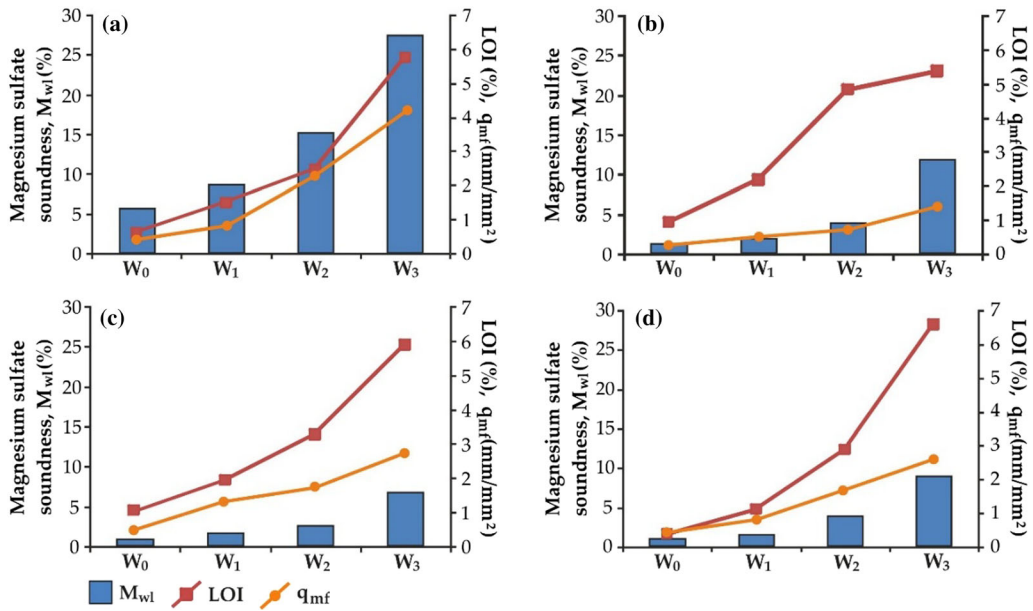
It should be, however, underlined that several complexities were confronted during the setup of AHP analyses. For instance, during the analyses for the criterion of  $C_1$ , it was observed that, although the gabbros had the highest value of  $t_2$ , its initial  $M_{wl}$  value was one of the lowest ( $M_{wl(W0)} = 0.83\%$ ) followed by granodiorites ( $M_{wl(W0)} = 0.74\%$ ). Such complexities were attempted to overcome by integrating such technical requirements and/or suggestions (Table 2) into the AHP analyses. The other difficulties were the interpretation of mineralogical variations and the weatherability trends of rocks. Due to the mineralogical variances of the rocks, especially for the criterion of  $C_5$ , it was quite difficult to assign a TLV that could be conformed to all rock types investigated in this study.

As to the TLV of  $q_{mf}$  ( $\leq 1.00 \text{ mm/mm}^2$ ), which was proposed to set over the criterion of  $C_5$ , it could be claimed that the  $q_{mf}$  could be utilized to come up with a relative measure to assess the rock aggregate quality from mineralogical and textural perspectives to some extent. However, it should be kept in mind that the variations in  $q_{mf}$  values are highly dependent upon the mineralogical composition of rocks. Therefore, the number of samples in rock types should be increased, and a satisfactory database is needed for further  $q_{mf}$  evaluations.

Having achieved immense differences in LOI values obtained in the rocks could not have the opportunity to let those values be integrated into the AHP analyses. However, the variations in LOI values could be regarded as a complementary parameter to support the criteria of  $C_1$  and  $C_5$  since similar trends were observed in  $M_{wl}$  and  $q_{mf}$  values (Fig. 10).

#### 4.5 Verification of the AHP Analyses

As seen in Table 11, it is obvious that the investigated rocks have been previously utilized for different



**Fig. 10** The variations in  $M_{wl}$ , LOI and  $q_{mf}$  values due to progressive rock weathering **a** Andesite **b** Basalt **c** Granodiorite **d** Gabbro

**Table 11** Summary of previous experiences on the industrial usage of the investigated rocks

Rock type	Practical use	Relative suitability of rock aggregate <sup>1</sup>	Reference
(a) Andesite	Coping/dimension stone	+ +	Erdoğan et al. (2012)
	Stone pitching	+	Kun (2013)
	Surface and sub-surface treatment <sup>II</sup>	+	Köken and Özarlan (2018)
	Concrete aggregate	+	
(b) Basalt	Coping/dimension stone	+ +	Aydın (2015)
	Stone dust/wool	+ + +	Doğruöz et al. (2016)
	Surface and sub-surface treatment	+ +	Köken and Özarlan (2018)
	Concrete aggregate	+ +	Bayhan and Bağcı (2018)
	Railway ballast	+ + +	Köken (2019)
(c) Granodiorite	Coping/dimension stone	+ + +	Erdoğan et al. (2012)
	Surface and subsurface-treatment	+ + +	Kun (2013)
	Concrete aggregate	+	Köken et al. (2016)
(d) Gabbro	Surface and sub-surface treatment	+ + +	Keserci (2014)
	Concrete aggregate	+ +	Arıoğlu (2015)
	Railway ballast	+ + +	Köken (2019)

*Note* The grading of the rock aggregate suitability was made, adopting the referenced publications, reports, and several personal communications who are experienced in the related rocks

<sup>1</sup>Relative suitability of the rock aggregates: Poor (+) Moderate (+ +) Good (+ + +)

<sup>II</sup>The surface treatment applications include rock aggregates used highways, stabilized and non-stabilized roads

purposes such as coping/dimension stone, surface and sub-surface treatment, concrete, and railway ballast materials. More deeply, the relative suitability of the gabbros is quite satisfactory for their previous uses (Keserci 2014; Arıoğlu 2015; Köken 2019). In contrast, the andesites seem to only be satisfactory for their use in coping/dimension stone (Erdoğan et al. 2012; Kun 2013; Köken and Özarlan 2018). The basalts could be of primary importance in the use of stone dust/wool and railway ballast material (Aydın 2015; Dođruöz et al. 2016; Köken and Özarlan 2016; Bayhan and Bađcı 2018; Köken 2019). The granodiorites could be considered as surface and subsurface aggregates in highways (Erdoğan et al. 2012; Kun 2013; Köken et al. 2016). The above-mentioned statements are only valid when the  $W_0$  type of rocks are considered. Otherwise, the suitability of rocks could be highly changeable.

Based on the previous experiences on the investigated rocks and their active use in different applications, it is logical to suppose that the AHP analysis results seem to be consistent with practical applications. Moreover, the analysis results also seem to be coherent when considering the CR values in Table 9. In other words, since all CR values in Table 9 were found to be less than 0.10, the AHP analyses could be admissible, according to Saaty (2008).

When comparing the interpolation methods used to correlate the RPs and CPs, although all interpolation methods considered in this study were found to be admissible, according to Saaty (2008), the exponential interpolation method provided lesser CR values. It, therefore, gave more reasonable results than the other

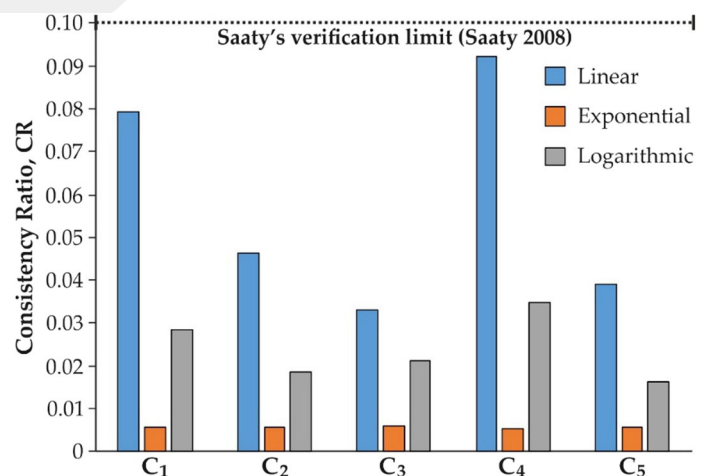
interpolation methods did (Fig. 11). Apart from the exponential interpolation, piecewise functions could also be beneficial for further AHP analyses, providing that the declaration of the technical superiority of rocks over one another is not easy to handle.

## 5 Conclusions

The present study introduces an AHP methodology for the evaluation of rock aggregate quality in terms of bituminous paving mixtures. For the AHP analyses, four rock types and five evaluation criteria ( $C_1$ – $C_5$ ) were established. The AHP analysis results indicate that the methodology followed in this study could be suitable for the evaluation of rock aggregate quality. The main results obtained from the present study could be drawn as follows:

- With progressive rock weathering, mineralogical features of LOI and  $q_{mf}$  increase remarkably (Table 6). For rapid estimations in assessing the weathering degree of the rocks investigated, the variations in Cl. m., Chl. and Zeo. minerals could be considered (Fig. 6). Those variables as a sign of rock aggregate quality could also be taken part in estimating the serviceability duration of rock aggregates.
- The rock aggregates properties of  $G_s$  decrease slightly, whereas the  $w_a$ ,  $M_{w1}$ , the  $S_{20}$ , and LAA increase considerably with progressive rock weathering (Table 7). Of these variables, the  $w_a$  and  $M_{w1}$  seem to be more prone to rock weathering

**Fig. 11** Comparison of different interpolation techniques considered in the AHP analyses



rather than other rock aggregate properties considered in this study. However, further efforts are needed to get a generalized inference of whether those variables would be the most sensitive rock aggregate properties to rock weathering processes.

- The AHP analyses reveal that different rock types have several advantages and disadvantages concerning various evaluation criteria. Therefore, the evaluation of rock aggregate quality through the AHP could enable mining companies to select and address proper rock types for various aggregate-based engineering purposes. Considering the AHP analyses, different environmental and mechanical conditions to which the rock could be exposed could also be represented by changing the relative weight of the evaluation criteria.
- Particular emphasis should be placed on minimizing/removing the quantity of weathered particles from the desired product by selective drilling–blasting and crushing–screening operations. Since rock masses with different weathering grades coexist, the adverse effects of rock weathering could be minimized by selective drilling–blasting and crushing–screening operations to some extent. In this way, the quality of rock aggregates could be improved, beginning from the manufacture to their service.

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#### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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