buildings

MDPI

Article

The Effect of the Microstructure of Diabases from Greece and Cyprus on Their Engineering Characteristics and the Mechanical Behaviour of Concrete

Petros Petrounias [1,*], Panagiota P. Giannakopoulou [1], Aikaterini Rogkala [1], Arsinoe Papalla [1], Vasileios Giamas [1], Paraskevi Lampropoulou [1], Petros Koutsovitis [1], Nikolaos Koukouzas [2] and Konstantin Hatzipanagiotou [1]

1 Section of Earth Materials, Department of Geology, University of Patras, 26504 Patras, Greece
2 Chemical Process & Energy Resources Institute, Centre for Research & Technology Hellas (CERTH), 15125 Athens, Greece
* Correspondence: geo.plan@outlook.com

Abstract: This article presents, for the first time, the study of diabases from various ophiolite complexes from Greece and Cyprus to identify their performance as concrete aggregates. Within this scope, in the first step, diabase samples from four selected ophiolite complexes of Greece (Veria-Naousa, Edessa and Guevgueli) and Cyprus (Troodos) were collected in order to estimate their suitability as concrete aggregates by means of their petrographic and physicochemical characteristics. In the next step, concrete specimens were prepared and their mechanical strength was measured in order to investigate their mechanical performance. Additionally, their petrographic characteristics in relation to the mechanical strength of the created concretes were investigated for the first time. Concrete specimens prepared by employing diabases from the Veria-Naousa and Guevgueli complexes as aggregates were reckoned as the most durable ones in contrast to those derived from the Edesssa complex and even more so than those from Cyprus, with the latter containing the most altered diabases (rodingitised). The overall conclusion of this research is that the engineering properties of the aggregates were dependent on their petrographic characteristics and hence they influenced the final mechanical behaviour of each produced concrete.

Keywords: concrete; engineering geology; diabase; Greece; Cyprus; aggregates

check for updates

Citation: Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Papalla, A.; Giamas, V.; Lampropoulou, P.; Koutsovitis, P.; Koukouzas, N.; Hatzipanagiotou, K. The Effect of the Microstructure of Diabases from Greece and Cyprus on Their Engineering Characteristics and the Mechanical Behaviour of Concrete. *Buildings* **2023**, *13*, 396. https://doi.org/10.3390/buildings13020396

Academic Editors: Roberto Capozucca and Elena Ferretti

Received: 9 December 2022
Revised: 19 January 2023
Accepted: 28 January 2023
Published: 1 February 2023

1. Introduction

Concrete is the most used building material worldwide [1,2]; it is implemented in buildings, highways, dams, bridges and generally in a variety of construction applications [3,4]. In recent times, rapid mechanisation, as well as urbanisation, has generated increasing demands for building materials, such as concrete and aggregates. It was estimated that the overall global demand for concrete is in excess of 20 billion tons per year. As a result, a massive demand for common aggregates and a reduction in material properties are generated [5,6]. According to this fact, there is also a great demand for finding more sustainable and eco-friendly construction materials [7]. Approximately 1 ton of concrete is produced for every person on Earth annually [8,9]. The annual growth in the concrete demand has exerted considerable pressure on the supply of constituent concrete substances to meet the continuous vast growing demand for concrete [10,11].

Concrete's main component is the material that binds the aggregate and commonly includes a mix of cement and water [12–14]. Structures built using concrete comprise hardened cement paste, aggregate and their interface [15,16]. The aggregates influence many of the concrete parameters [17] by offering remarkable advantages to concrete from a technical point of view. They positively affect the static behaviour of concrete structures, ensure great volume stability and extend the "life service" of structures compared with the use of cement mortar only. Additionally, aggregates are present in high amounts ranging between 70% and 80% in concrete specimens.

The main coarse type of concrete aggregates indicates the main factor for concrete quality for many researchers, as well as for industries. For similar quality cement, variable lithotypes of coarse aggregates are characterised by a variety of modal mineralogy, micro-roughness and compressive strength, resulting in diverse concrete compressive strengths [18,19]. The primary and secondary mineralogy (alteration products) of the aggregate rocks can highly affect their mechanical behaviour and their in-service performance [19–25]. The presence of relatively high percentages of specified secondary minerals can lead to negative effects on the engineering properties of aggregates because of their cleavage, platy or fibrous crystal habit and smooth layers [19,25], leading to a poor influence on their general behaviour as concrete aggregates [19]. Numerous failures pointed out the importance of denoting that detailed mineralogical studies may significantly assist in identifying problems in engineering constructions. Physicomechanical properties are determined by petrographical characteristics [26–30]. The aggregates can be considered to have poor, marginal or premium quality depending on the physicomechanical features of the natural material, the mineralogy composition, the microroughness, the processing operation and the final general engineering characteristics. Aggregates of poor quality are often regarded as unsuitable for concrete and marginal-quality aggregates do not comply with many traditional contract specifications. However, using stabilisation, the marginal quality aggregate performance properties similar to or even better than those of premium quality aggregates can be achieved [12,31]. Many studies indicated an evident association between the differences in coarse-sized aggregates along with differences in the final concrete's performance and possible failures [16,18–20]. Those materials may be classified into fine or coarse relative to the particle size distribution [32]. Fine aggregates are most often natural soil sand or selected from riverbanks. Mishuk et al. [33] pointed out the coarse aggregates' maximum size that tends to be suitable for concrete.

Up to now, there were numerous studies [18,34–38] that dealt with the examination of the influence of various lithologies of rocks used as aggregates but there are not so many that have dealt with the correlations amongst different types of aggregates upon concrete strength (i.e., [19,39]). Özturan and Çeçen [40] presented how a coarse aggregate may influence the mechanical behaviour of concrete: the concrete made using basalt and gravel provided similar compressive strengths, while concrete made with limestones with the same size of aggregate presented better mechanical behaviour. Other scientists, such as Yilmaz and Tugrul [18], demonstrated that concrete specimens made using subarkose aggregates display nearly 40–50% better mechanical behaviour in contrast to those made using several types of aggregates; at the same time, they found that the mineralogy and microtopography of the aggregate particles constituted crucial parameters for the adherence of the cement paste with the aggregate [19]. The occurrence of high microtopography in the aggregate materials correlated with the occurrence of secondary phyllosilicate minerals, and the variety of minerals' hardness is related to the cohesion between rocks and cement paste. This fact also leads to concrete specimens of higher quality. Diabases or dolerites are medium-grained igneous rocks that display a mineralogical composition similar to that of basalt and, most of the time, they are found in dykes or sills. The physical, chemical and mechanical behaviours of diabase make this rock a versatile material, which can be used as a crushed aggregate for concrete production and in numerous other applications [15]. Petrounias et al. [41] investigated several rock samples that were selected either from ophiolite complexes (mafic and ultramafic rocks) or their surrounding rocks. The results showed that concrete specimens produced by diabase aggregates displayed more than satisfactory mechanical behaviour due to the optimal cohesion between the selected rocks and cement. Optimal bonding resulted in the petrographical characteristics of these lithologies, which played a critical role in both the engineering properties of the rocks and, consequently, the final concrete uniaxial compressive strength [39,41].

The main scope of the investigation constituted the study and the comparison of diabases from various ophiolite complexes in Greece and Cyprus and to identify their suitability as concrete aggregates. Additionally, another goal of this study was to enrich and fill the research gap regarding a great number of laboratory tests and results from various rocks derived from Greek ophiolite complexes that are used as aggregate rocks. For this purpose, concrete specimens were prepared and studied in order to identify the interdependence of the petrographic characteristics of the diabases with the final mechanical performance of the produced concretes and, consequently, their behaviour.

2. Geological Settings (Greece and Cyprus)

In the present study, sampling and mapping diabase outcrops were performed in three ophiolite complexes in Greece and one ophiolite complex in Cyprus in order to evaluate their use in concrete applications.

2.1. Veria-Naousa Ophiolites (Greece)

The Veria-Naousa ophiolites were assigned to the Almopias geotectonic subzone. This complex mainly consists of mantle lherzolite and harzburgite with variable degrees of serpentinisation that are cut by scarce pyroxenitic dykes [42,43], gabbro, diabase and pillow basalt (Figure 1).

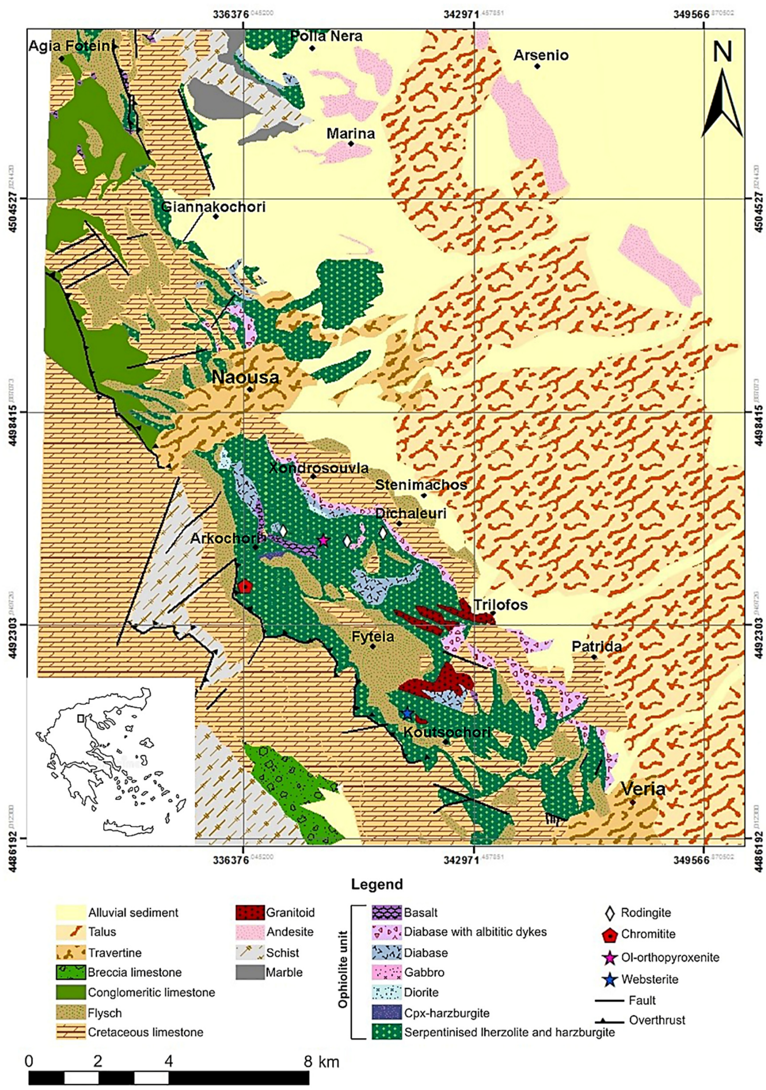

Figure 1. Modified geological map of the Veria-Naousa region [44–46]; the rectangle in the inset shows the study area.

2.2. Edessa Ophiolites (Greece)

This complex contains the remnants of the oceanic lithosphere that represent the closure of one or even two oceanic basins during the Upper Jurassic to Lower Cretaceous time [47–49]. This complex comprises intense serpentinised peridotites, such as lherzolite; harzburgite; and mafic rocks, such as gabbro, diabase, basalt and diorite (Figure 2).

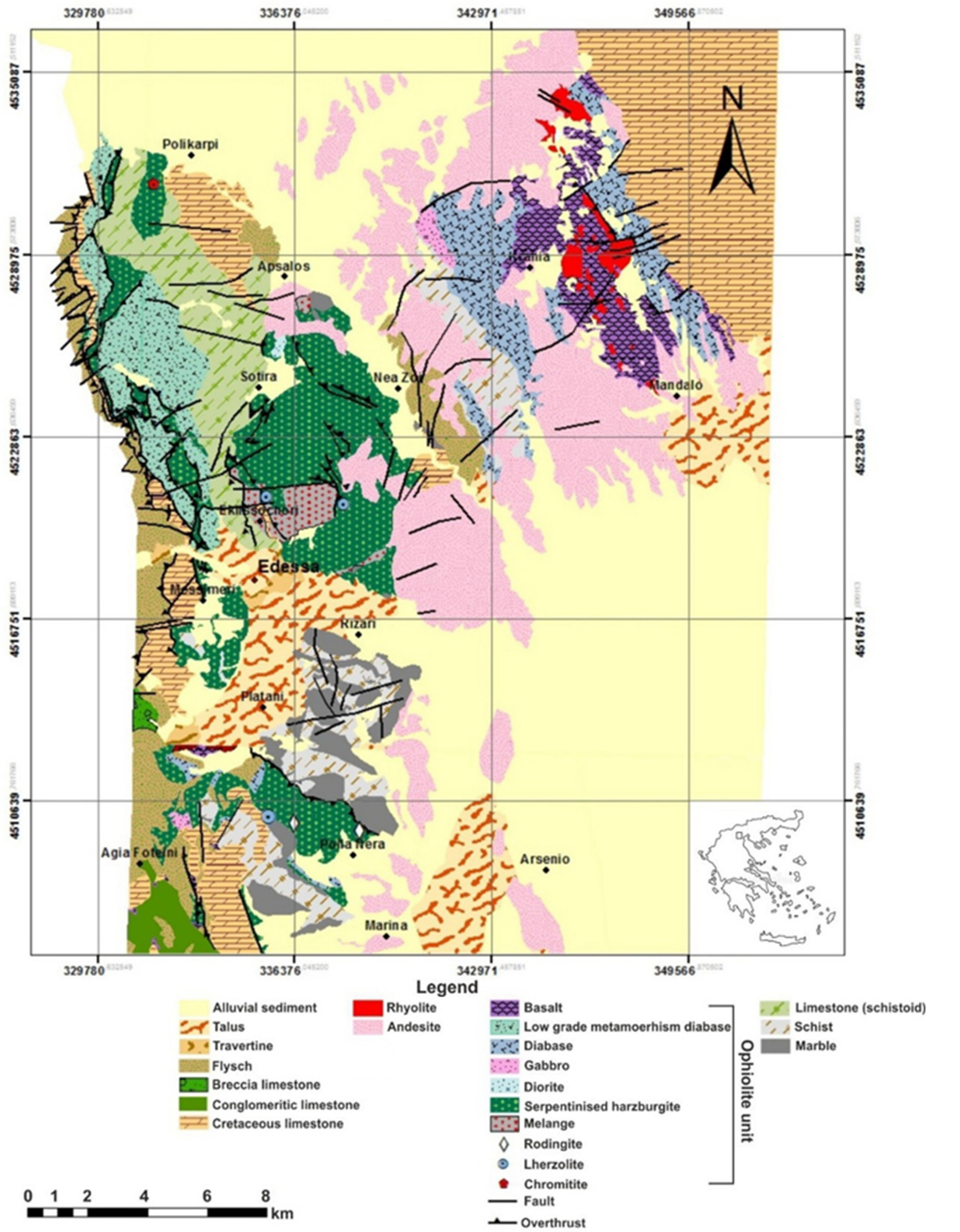

Figure 2. Modified geological map of the Edessa region [50,51]; the rectangle in the inset shows the study area.

2.3. Guevgueli Ophiolite Complex (Greece)

The western and eastern sub-units of this ophiolite complex include olivine and amphibole gabbro, as well as diorite and diabase (Figure 3) [52,53].

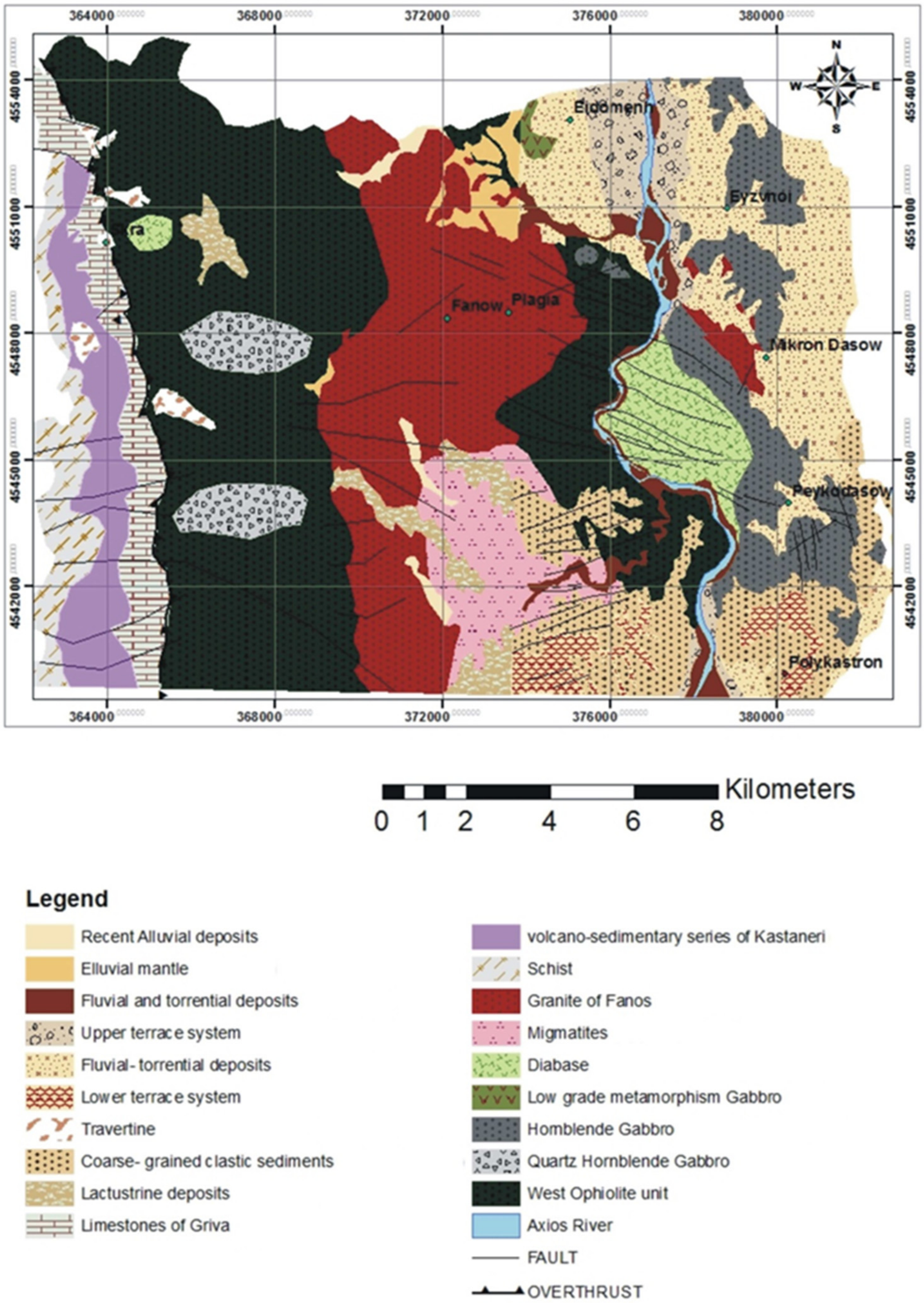

Figure 3. Modified geological map of the Guevgueli region [54,55].

2.4. Troodos Ophiolite Complex (Cyprus)

Based on the biostratigraphy of the oldest sediments it encompasses, the Troodos ophiolite complex dates back to approximately the mid-late Cretaceous Turonian to Maastrictian age (Figure 4) [56]. The quarry area of Parekklisia where the examined rocks came from was 20 km northeast of the city of Limassol. The sheeted dyke complex (diabase) was created via the solidification of the magma in the channels. The magma was inserted due to magma chambers located at the oceanic crust's bottom while also being fed by submarine lava's extrusions at the seafloor. These intrusive rocks have fine-to-medium coarseness, are crystalline and exhibit a basaltic-to-diabasic composition (Cyprus Geological Survey Department).

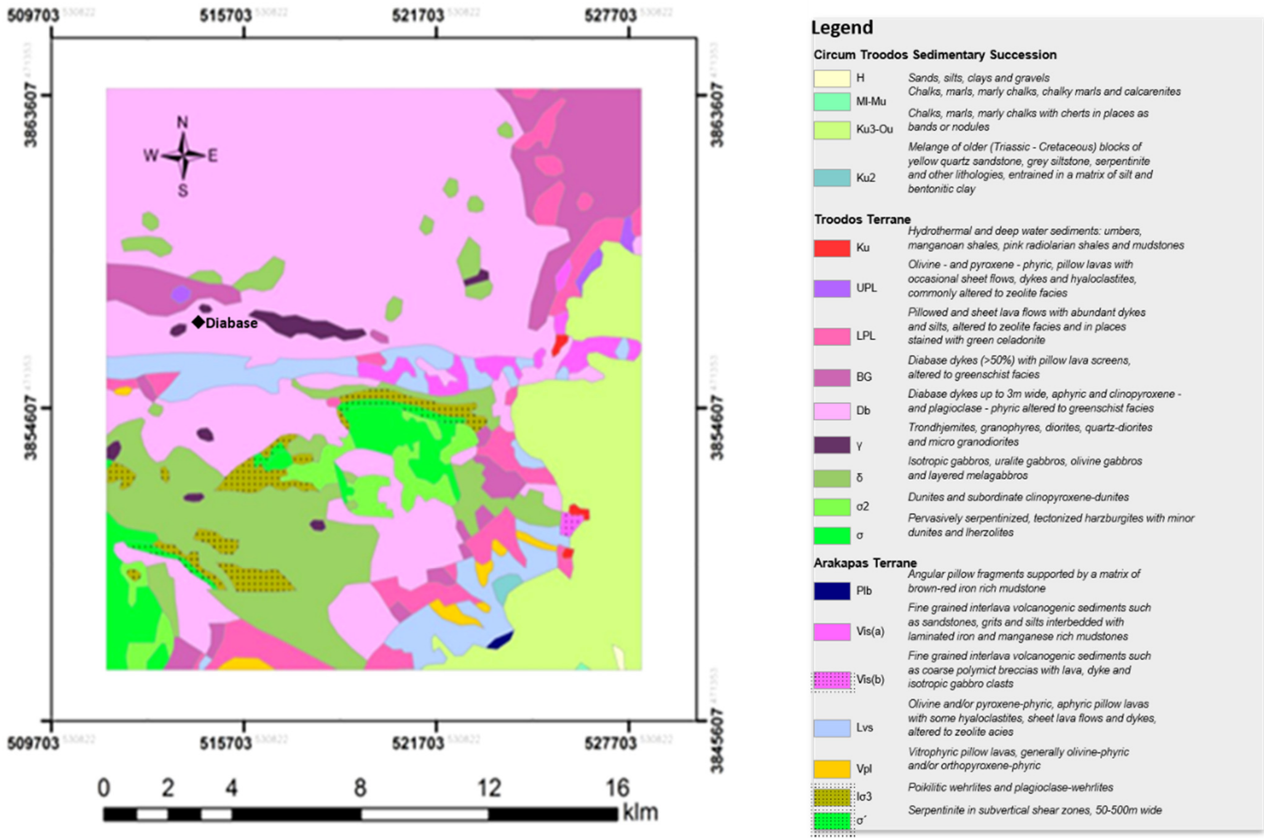

Figure 4. Digital map in the study area of the Quarry of Parekklisia (Geological Survey Department).

3. Materials and Methods

3.1. Materials

Diabases of the four ophiolite complexes (Cyprus and Greece) were studied according to their petrographic, physical, mechanical and physicochemical characteristics in terms of their use as concrete aggregates. Moreover, we examined how their characteristics varied from one ophiolite complex to the other and how these characteristics influenced the final concrete mechanical behaviour. More specifically, three samples from each ophiolite complex were collected and two cubic concrete specimens (15 × 15 cm) were prepared.

3.2. Methods for the Aggregates

The tested aggregates were suitably prepared for both engineering tests and for their petrographic characterisation. The tests and the petrographic analytical methods that were performed in this study are given in the table below (Table 1).

Table 1. Aggregate tests and analytical methods for petrographic characterisation.

Tests/Analytical Methods	Standards
Moisture content (w)	AASHTO T-255 [57]
Total porosity (n_t)	ISRM 1981 [58]
Specific gravity (ρ_d)	ISRM 1981 [58]
Water absorption (w_a)	ISRM 1981 [58]
Elongation index (I_E)	BS 812 1989 [59]
Flakiness index (I_F)	BS 812 1990 [60]
Los Angeles abrasion value (LA)	ASTM C-131 [61]
Uniaxial compressive strength (UCS).	ASTM D 2938-95 [62]
Soundness test (S)	EN 1367-2 standard [63]
Mineralogical and microstructural characterization using a polarizing microscope	EN-932-3 [64]
Semi-qualitative calculations of mineral phases using XRD	Bish and Post [65]
Surface texture study through SEI	BS 812 Part 1 [66]

More specifically, the tested rocks were crushed into suitable sizes. Then, cylindrical specimens were prepared in the laboratory, where the diameters varied between 50 and 54 mm and the length to diameter ratio varied between 2.2 and 2.5. In the studied samples, the moisture content (w) was calculated according to the AASHTO T-255 standard [57], and the total porosity (n_t), water absorption (w_a) and specific gravity (ρ_d) were determined according to ISRM 1981 [58]. The flakiness index (I_F) [59] and elongation index (I_E) constituted the geometrical properties that were determined [60].

Regarding the mechanical behaviour of the rocks, the Los Angeles abrasion (LA) was identified in accordance with the ASTM C-131 standard [61]. Moreover, the uniaxial compressive strength (UCS) was also identified according to the ASTM D 2938-95 [62]. As for the physicochemical properties, the soundness test (S) was conducted according to the EN 1367-2 standard [63]. The mineralogical and microstructural characteristics were observed in polished thin sections with a polarising microscope (Leitz Ortholux II POL-BK Ltd., Midland, ON, Canada) following the EN-932-3 [64] standard. Specifically, they were examined for the types of grains, mean grain size and grain shape. In the next step, their mineralogy was examined via X-ray diffraction (XRD) using a Bruker D8 Advance diffractometer, with Ni-filtered CuKα radiation, covering the interval of 2–70° 2θ, with a step size of 0.015°/0.1 s. The contained minerals were found with the aid of the DIFFRAC plus EVA 12® software (Bruker-AXS, Gmbtl, Karlsruhe, Germany) based on the ICDD Powder Diffraction File of PDF-2 2006. Furthermore, their modal mineralogy was also semi-quantitatively calculated through the Rietveld method according to Bish and Post [65]. The microtopography of the diabases was identified by using secondary electron images (SEI) (BS 812 Part 1 [66]), outlining seven qualitative categories, namely, granular, smooth, rough, honeycomb, crystalline, glassy and porous, with the aid of a JEOL JSM-6300 SEM equipped with energy dispersive and wavelength dispersive spectrometers and INCA software.

3.3. Methods for the Concretes

Twenty-four normal concrete cube specimens (150 × 150 mm) were prepared from the various aggregate types (Table 1) with the aid of the ACI-211.1-91 standard [67]. The first step was to crush the aggregates into the 2.00–4.75, 4.45–9.5 and 9.5–19.1 mm size classes. The second step was the removal of the samples, from the mold after 24 h and their curation in water for 28 days (temperature: 20 ± 3 °C). The third step was the identification of the compressive strength test of the specimens according to BS EN 12390-3:2009 [68].

Following the compressive strength tests of the cubic specimens, the textural characteristics of the concretes were identified in the fourth step. For this reason, using a polarising microscope, polished thin sections were studied in accordance with the ASTM C856-17 standard [69]. The final step included the 3D depiction of the petrographic features of the specimens using the 3D Builder software.

4. Results

4.1. Petrographic Features of the Rock Samples

The Veria-Naousa diabases consisted of sand and compacted diabase rocks that were intruded by albititic dykes. The former rocks exhibited porphyritic (large crystals in a microcrystalline matrix) and subophitic textures where a network of mineral interstices was filled with other components (Figure 5a). More coarse crystals were rare and they comprised subheral clinopyroxene and fine-grained plagioclase. Magnetite, ilmenite and titanite were accessory minerals. Other secondary minerals were sericite, chlorite, albite, epidote, fibrous amphibole (mostly actinolite) and titanite. The compacted diabases displayed comparable textures (Figure 5b), with their primary assemblage comprising plagioclase, clinopyroxene, magnesiochromite and magnetite.

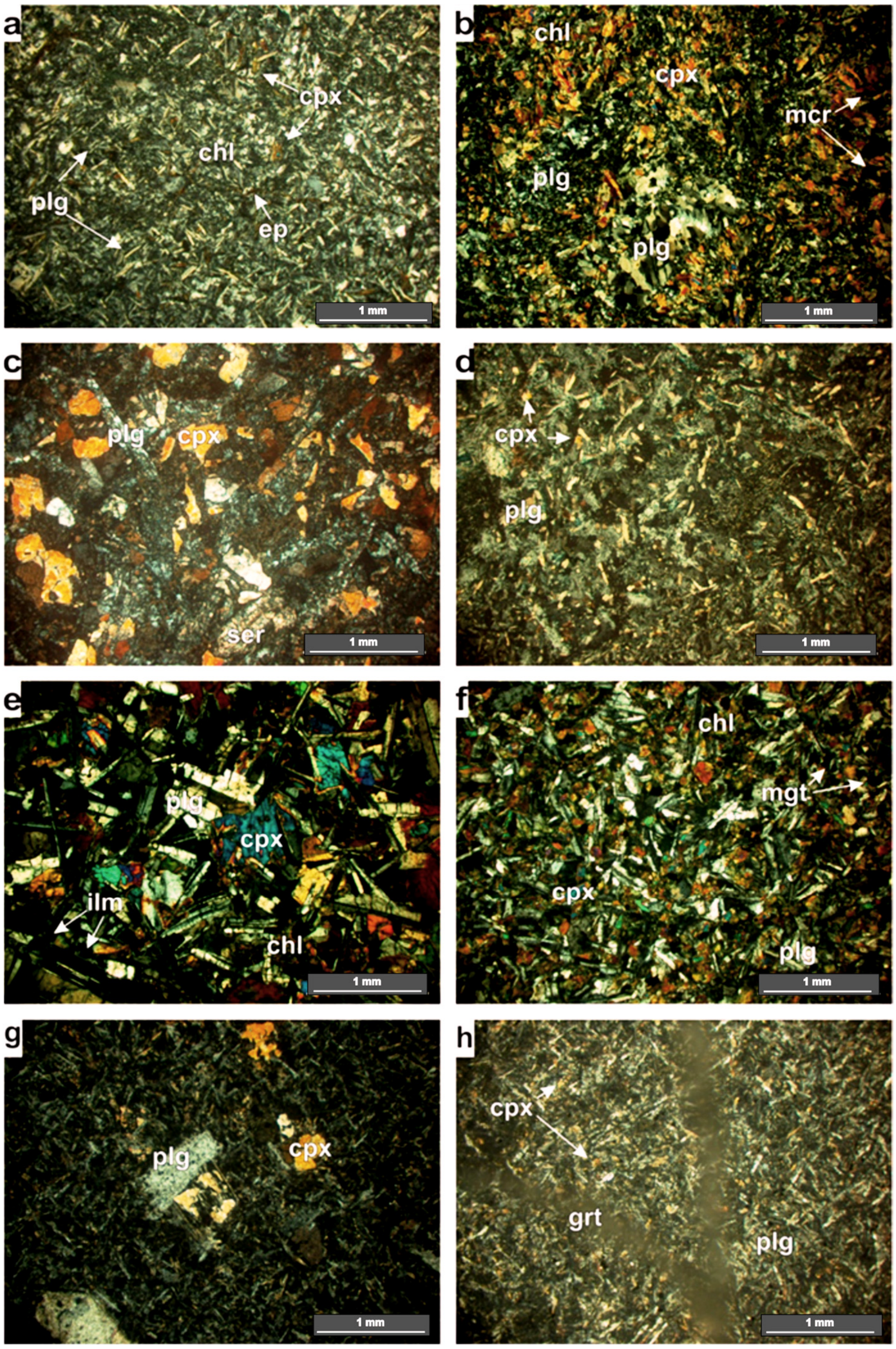

Figure 5. Photomicrographs of representative diabase samples (XPL). (**a**) Subophitic texture with plagioclase and clinopyroxene, where clinopyroxene was altered to epidote and chlorite (sample BE.24). (**b**) Fine-grained and coarse-grained idiomorphic plagioclase (sample BE.43). (**c**,**d**) Subophitic texture with clinopyroxene and plagioclase altered to sericite (samples ED.66B and ED.110, respectively). (**e**) Irregular plagioclase and clinopyroxenen that formed an ophitic texture accompanied by subhedral grains of ilmenite and chlorite (sample KIL.2). (**f**) Subophitic texture along with plagioclase, clinopyroxene altered to chlorite and a few crystals of magnetite (sample KIL.3). (**g**) Porphyroid texture along with plagioclase and clinopyroxene (sample PR1). (**h**) Fine-to-medium-grained subidiomorphic crystals of garnets that formed granoblastic segregations and a subophitic texture (sample PR2). Abbreviations: ep—epidote, cpx—clinopyroxene, chl—chlorite, plg—plagioclase, mcr—magnesiochromite, ser—sericite, ilm—ilmenite, mgt—magnetite, grt—garnet.

The samples derived from the Edessa ophiolites exhibited porphyroid, ophitic and subophitic textures (Figure 5c,d). Their modal mineralogy consisted of clinopyroxene and subhedral plagioclase. The plagioclase was partially or completely replaced by sericite in some rocks (Figure 5c). Titanite, magnetite and ilmenite were also observed in small amounts. Actinolite, epidote, prehnite, chlorite and calcite were interpreted as secondary phases.

The diabases derived from the Guevgueli ophiolite complex displayed comparable textural features with the diabases from the Edessa ophiolite (Figure 5e,f). Their primary assemblages consisted of clinopyroxene and plagioclase. Plagioclase was partially altered to minor sericite. Ilmenite, magnetite, titanite and zircon were present in smaller amounts.

Chlorite, epidote, prehnite and actinolite were the secondary minerals observed. Chlorite was presented in a uniform distribution, while in some cases, it occupied the interstices in the matrix.

The primary mineralogy of the diabase derived from Cyprus (Troodos ophiolite complex) encompassed plagioclase that was mostly albite, as well as clinopyroxene (Figure 5g,h). Chlorite and garnet in smaller amounts represented the secondary mineralogy. Regarding the textural features of these diabase samples, they mainly displayed ophitic and less often subophitic and porphyroid textures. The presence of garnet and chlorite indicated that these samples were affected to some extent via rodingitisation as a basic type of alteration in these samples. Garnet presented as coarse- and idiomorphic-grained and exhibited cataclastic textural features (Figure 5h).

4.2. Rock X-ray Diffractometry

XRD results containing the mineralogical compositions of the tested aggregates are shown in Figure 6 and Table 2, where the primary and secondary mineralogical assemblages are shown. The main secondary minerals were actinolite and chlorite, the concentrations of which ranged from 6.8 to 33.2% and 7.2 to 23.3%, respectively. We should also mention that in the diabases derived from Cyprus, the primary stages of rodingitization were observed.

Table 2. Mineralogical compositions of representative diabasic samples (-: not detected). The quantification errors calculated for each phase according to Bish and Post [65] were estimated to be ~1%. Abbreviations: cpx—clinopyroxene, qz—quartz, plg—plagioclase, Kfs—K-feldspar, bi—biotite, ttn—titanite, ilm—ilmenite, mgt—magnetite, ap—apatite, ser—sericite, chl—chlorite, act—actinolite, ep—epidote, prh—prehnite, grt—garnet.

Samples	BE.113	BE.43	ED.45	ED.110	KIL.2	KIL.3	ED.66B	BE.24	PR1	PR3
cpx	-	6.6	15.5	3.1	25.9	19.4	29.2	13.1	22.0	20.0
qz	-	6.0	7.0	2.1	5.1	4.2	-	9.4	-	-
plg	59.1	47.0	46.0	46.0	39.9	51.1	52.0	33.6	44.0	45.0
Kfs	-	-	-	-	-	1.3	-	-	-	-
bi	-	-	5.1	-	-	-	-	-	-	-
ttn	2.3	2.5	-	-	1.7	0.9	3.0	1.8	4.5	3.5
ilm	-	-	-	-	-	-	-	2.9	-	-
mgt	-	4.0	-	-	-	-	-	-	-	-
ap	-	2.4	-	-	-	-	-	-	-	1.2
ser	-	-	-	-	-	-	-	5.8	-	-
chl	18.0	10.0	19.0	7.2	9.6	7.2	15.8	13.6	22.0	23.3
act	20.6	15.0	-	33.2	6.8	9.4	-	11.1	-	-
ep	-	6.5	7.4	8.4	11.0	6.5	-	4.4	-	-
prh	-	-	-	-	-	-	-	4.3	-	-
grt	-	-	-	-	-	-	-	-	7.5	7.0

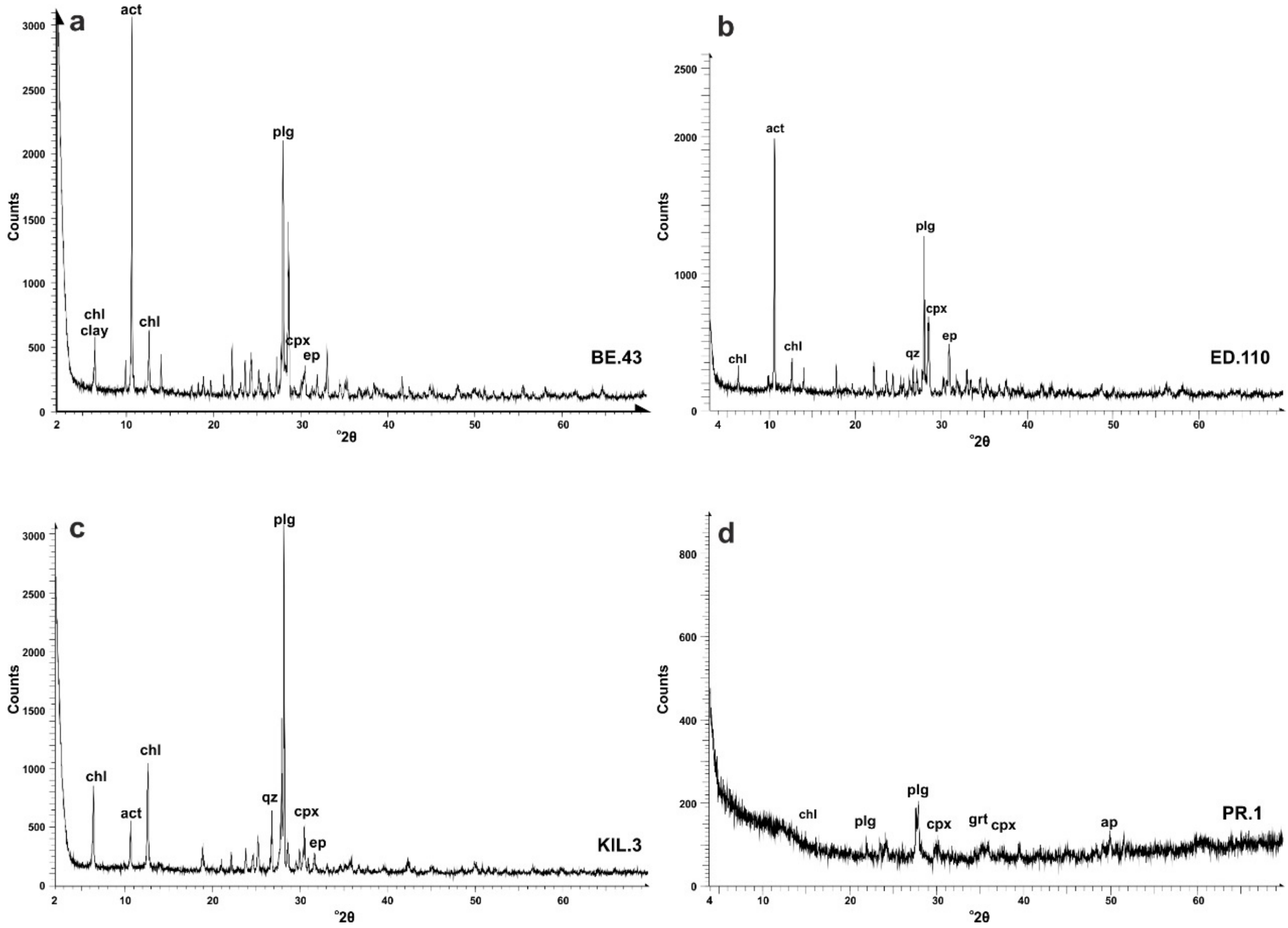

Figure 6. XRD analysis results of representative studied samples. (**a**) Diabase from the Veria-Naousa ophiolite complex (Greece). (**b**) Diabase from the Edessa ophiolite complex (Greece). (**c**) Diabase from the Guevgueli ophiolite complex (Greece). (**d**) Diabase from the Troodos ophiolite complex (Cyprus). Abbreviations: chl—chlorite, clay—clay minerals, act—actinolite, plg—plagioclase, cpx—clinopyroxene, ep—epidote, qz—quartz, grt—garnet, ap—apatite.

4.3. Microtopography of the Studied Diabases

The aggregate's microroughness observations further enhanced the microscopic observations of diabases derived both from Greece and Cyprus, which allowed for extracting more robust conclusions regarding their performance in concrete. As displayed in Figure 7a–c, the diabases derived from Greece presented higher microtopography than those found in Cyprus. Specifically, sample PR.1 from the Troodos ophiolite complex (Figure 7d) displayed smooth surfaces that were likely due to the high abundance of garnet. The first three diabase samples (Greece) displayed rough textures that were most probably due to the presence of juxtaposed clinopyroxene, actinolite and plagioclase combined with chlorite. The continuous change in either smooth or flatty minerals formed a variety in the microtopography of the Greek diabase rock samples, which consequently promoted better cohesion between the cement and rocks in the concrete specimens [19].

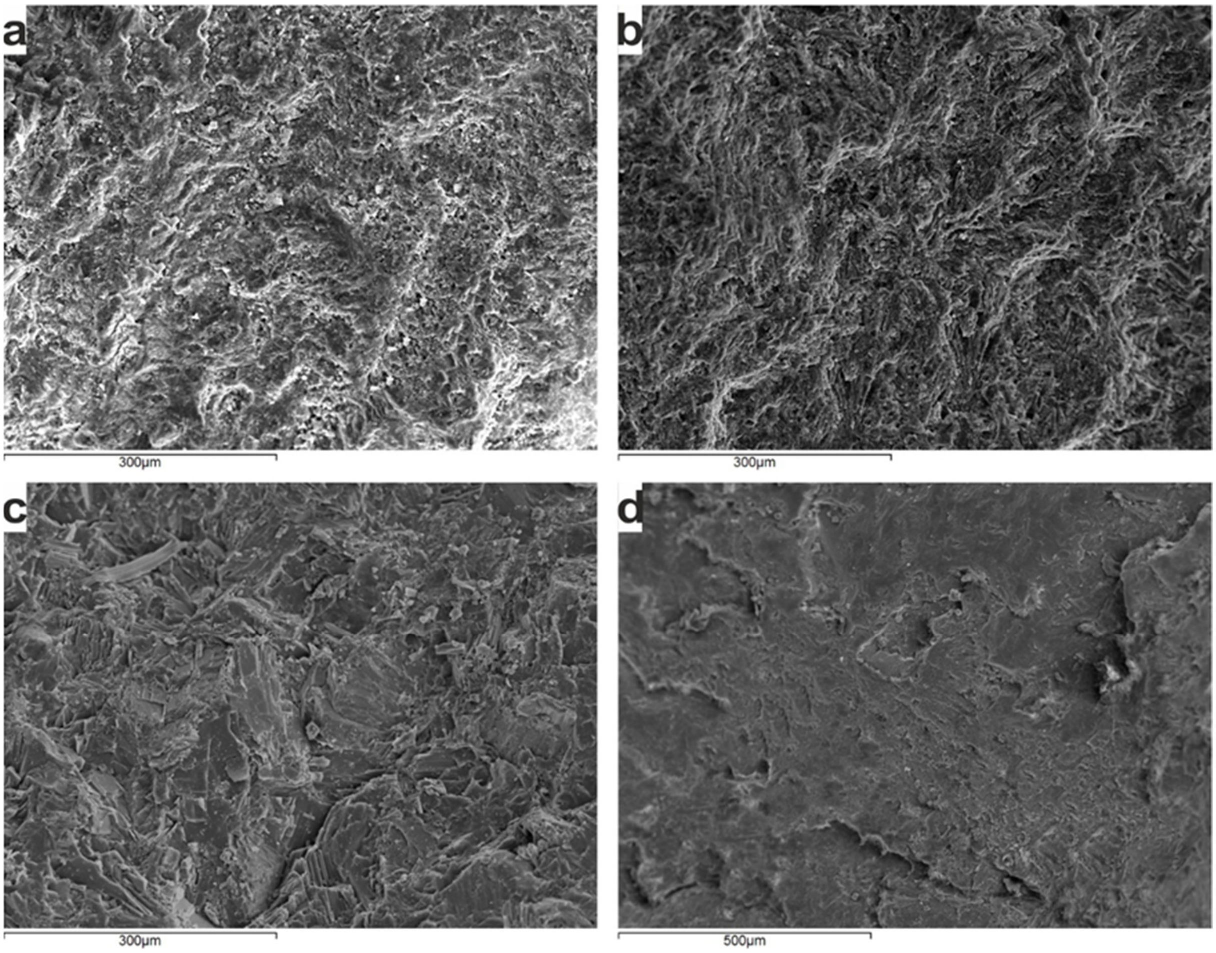

Figure 7. Secondary electron images (SEI) showing the surface texture of representative studied diabases. Differences in the mineralogical and textural features were also observed. (**a**) Diabase from the Veria-Naousa ophiolite complex (sample BE.43). (**b**) Diabase from the Edessa ophiolite complex (sample ED.110). (**c**) Diabase from the Guevgueli ophiolite complex (sample KIL.2). (**d**) Diabase from the Troodos ophiolite complex (sample PR.1).

4.4. Engineering Properties of the Aggregates

The most significant engineering properties that may influence the mechanical behaviour of concrete are displayed in Table 3. Regarding the values in Table 3, the moisture content values ranged from 0.14 to 1.40%, in which the lowest value was recorded in a lowly altered diabase from the Guevgueli ophiolite complex, whereas the highest value was observed in a diabase sample from Cyprus. Moreover, the water absorption and specific gravity were determined. The values of water absorption ranged from 0.35 to 3.25%, while the specific gravity presented values ranging from 23.20 to 28.80 KN/m^3. Regarding the flakiness index (I_F), the values ranged from 15.79 to 46.17%, with both the highest and the lowest values encountered in samples derived from the Edessa complex. The elongation index (I_E) presented values ranging from 9.80 (Veria-Naousa complex) to 44.77% (Guevgueli complex). The diabases derived from the Edessa ophiolite complex presented higher resistance regarding abrasion and attrition (7.31%), while the diabases from Cyprus were less resistant to abrasion and attrition (up to 18.00%). The UCS of the total of the investigated samples fluctuated considerably following their values in the LA test. More specifically, the lowest mechanical strength was observed in the diabase samples from Cyprus (61.0 MPa), whereas the highest mechanical strength was noticed in those from the Edessa complex (150.0 MPa). The soundness test results ranged from 2.02 (Veria-Naousa) to 8.00% (Cyprus).

Table 3. Results of the physicomechanical and geometrical properties of the tested diabases.

Samples	W (%)	ρ_d (KN/m^3)	w_a (%)	IF (%)	IE (%)	LA (%)	UCS (MPa)	S (%)
KIL.2/Guevgueli	0.20	28.80	0.86	31.67	34.73	9.31	122.3	3.71
KIL.3/Guevgueli	0.14	28.35	0.84	36.91	44.77	10.77	126.7	2.52
BE.24/Veria	0.44	27.69	0.82	33.30	9.80	11.34	124.6	3.45
BE.43/Veria	0.25	26.57	0.38	31.30	16.60	8.72	150.0	3.74
ED.24/Edessa	0.52	25.40	0.36	15.79	19.68	14.15	91.30	3.58
BE.113/Veria	0.42	25.30	0.35	24.05	14.00	12.00	97.20	2.02
ED.45/Edessa	0.41	26.66	0.40	29.93	16.00	9.99	110.0	3.12
ED.66B/Edessa	0.50	27.75	0.80	46.17	17.00	8.18	119.0	2.47
ED.110/Edessa	0.20	27.36	0.48	24.88	17.80	7.31	148.0	3.96
PR1/Cyprus	1.40	24.00	2.71	20.14	36.75	17.00	62.0	8.00
PR2/Cyprus	0.80	23.20	3.25	19.50	31.56	17.00	70.0	5.50
PR3/Cyprus	1.00	24.50	2.80	18.00	35.00	16.00	74.0	5.20
PR4/Cyprus	0.90	23.40	2.76	20.00	36.40	18.00	61.0	6.50
BE.180/Veria	0.45	27.00	0.83	32.50	9.78	11.50	125.0	3.60
KIL.11/Guevgueli	0.21	28.70	0.80	31.59	34.70	9.40	122.0	3.70
KIL.12/Guevgueli	0.19	28.55	0.82	34.50	35.50	10.20	123.0	3.20

4.5. Mechanical Properties of the Concrete Specimens

The concrete UCS test results showed that the concrete produced using the Veria-Naousa and Guevgueli diabases displayed optimal strength values (32.0 to 33.0 MPa), while those made using diabases from the Edessa ophiolite complex presented lower strength values (Table 3). The concrete specimens made using diabasic sample ED.110 constituted an exception since they showed higher strength values similar to those from the Veria-Naousa and Guevgueli ophiolite complexes. Regarding concrete specimens produced using diabases from Cyprus, they were the least durable amongst all of the tested samples (26.0 to 29.0 MPa) (Table 4).

Table 4. Results of the uniaxial compressive strength test (UCS_{con}) of the produced concrete specimens.

Samples	UCS_{con} (MPa)
KIL.2/Guevgueli	32.0
KIL.3/Guevgueli	32.0
BE.24/Veria	32.0
BE.43/Veria	33.0
ED.24/Edessa	31.0
BE.113/Veria	31.0
ED.45/Edessa	31.0
ED.66B/Edessa	31.0
ED.110/Edessa	32.0
PR1/Cyprus	26.0
PR2/Cyprus	29.0
PR3/Cyprus	28.0
PR4/Cyprus	27.0
BE.180/Veria	32.0
KIL.11/Guevgueli	32.0
KIL.12/Guevgueli	31.0

4.6. Microscopic Features of the Concrete Specimens

The performance of the produced concrete specimens and the cohesion between the used rocks and the cement paste were studied by means of a petrographic study of the thin sections made with concrete specimens by using a polarising microscope (Figure 8). Regarding the concrete specimens produced with diabases from the Veria-Naousa and Guevgueli regions, they presented considerably better bonding between the diabases and the cement paste (Figure 8a,b,e,f) than those derived from the Edessa ophiolite complex (Figure 8c,d), where all of the collected samples presented local failures and microcracks due to the higher abundance of secondary minerals, especially chlorite. The specimen produced using the aggregate ED.110 was presented as the exception of this ophiolite complex since it showed good cohesion and similar features to that of the Veria-Naousa and Guevgueli ophiolite complexes. Careful microscopic observation revealed that concrete specimens produced using the diabases from Cyprus (Figure 8g,h) displayed the majority of the failures and microcracks among all the produced specimens, triggering defects and weaknesses in them. In Figure 8g,h, the local de-bonding between the diabase and the cement is shown.

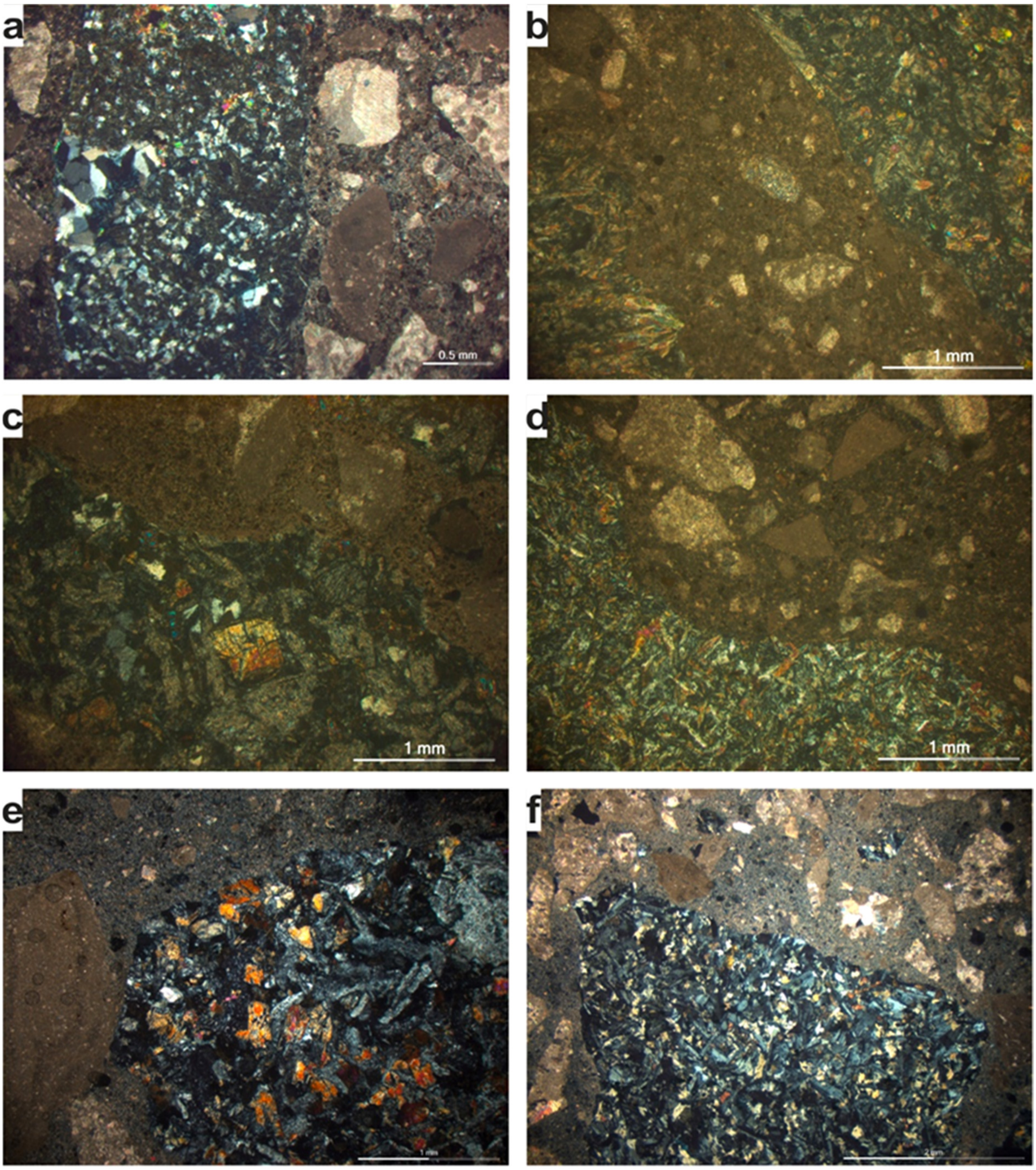

Figure 8. *Cont*.

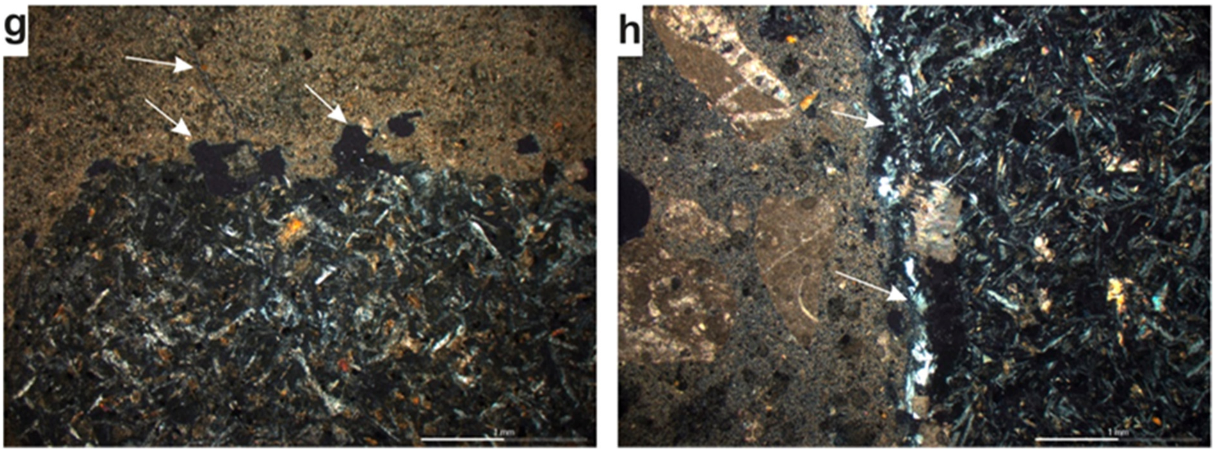

Figure 8. Photomicrographs of representative tested concrete specimens derived from all the studied ophiolite complexes (all under XPL). (**a**,**b**) Good cohesion between the cement paste and the diabases used as concrete aggregates and derived from the Veria-Naousa ophiolite complex. (**c**,**d**) Diabases from the Edessa ophiolite complex presented strong bonding with the cement paste of the respective produced concrete specimens. (**e**,**f**) Satisfactory cohesion between the cement paste and the diabases used as concrete aggregates and derived from the Guevgueli ophiolite complex. (**g**,**h**) Concrete specimens made using the diabases from Cyprus showed failures and gaps between the aggregates and cement.

5. Discussion

Nowadays, the interest in the identification of the specific effects of aggregates on the final behaviour of constructed materials, especially concrete, is increased, as the prediction of the behaviour of the aggregates in a construction constitutes a sustainable solution that is necessary for society. Many researchers reported that the type of aggregates directly, either natural [21,39,41,70,71] or recycled [72–74], affects both the aggregate properties and the final products (i.e., concrete) depending on their microstructure. The mineralogical composition, texture and alteration phenomena of aggregate rocks are crucial parameters that determine their engineering character, and hence, the final mechanical behaviour of constructions. According to many research studies, a significant parameter of mafic aggregate rocks is the aggregate type and the amount of secondary phyllosilicate minerals contained. The different lithologies of an ophiolite present a variety of mineralogical compositions and textural features. Therefore, it is common for lithologies to give different mechanical results, even within the same suite. The present study focused on the investigation of exclusively diabase rocks from well-known ophiolites of Greece and Cyprus since these are the main raw materials for the production of high-quality and durable concrete in both countries. The main novelty of this study was that by taking into account a great number of data on diabasic rocks, their engineering properties could be predicted with respect to each other and the mechanical behaviour of the produced concrete could be predicted through these properties, which directly depended on the micropetrographic characteristics of the aggregate rocks. The engineering parameter values of the aggregates and their respective concrete indicated that the diabases generally behaved in a satisfactory manner as aggregates, particularly as aggregates in concrete. The overall results of the physical properties of the rocks (w, n_t, w_a, ρ_d) used as aggregates were suitable regarding their use as concrete aggregates. However, significant differences were found between the studied diabases that directly depended upon the ophiolite complex where they came from and were apparently directly influenced by their particular mineralogical characteristics.

5.1. Correlation Analysis between the Engineering Properties of the Investigated Diabases

The study of the investigated diabasic samples from the studied ophiolite complexes in correlation with their physicomechanical properties revealed the direct dependence of the properties between them. Regression analysis was applied regarding the physicomechanical properties of the diabases, with 95% confidence limits. The possible R^2 values range from 0 to 1, where the values that tend towards the value 1 show the strongest correlations. Similar correlations between the engineering properties of the aggregates and between the aggregates and the engineering properties of the produced concrete specimens were performed by numerous scientists (i.e., [20–26,39]).

The connection between the physicomechanical and physicochemical parameters is of particular importance, as it allows for both the understanding of how the properties change and the identification of strong trends that make it possible to estimate one parameter based on another. Correlations between the engineering properties were reported by several research studies, where they were interpreted based on their particular mineralogical characteristics, as the correlation analysis constituted a more accurate and eco-friendly method to check the aggregate qualities. The relationship between the mechanical strength and the aggregate's petrography was generally discussed and addressed by Rigopoulos et al. [21] and Petrounias et al. [19,25,73]. Specific investigations on the subject are sparse, and thus, each extra study enhances the corresponding literature. Gunsallus and Kulhaw [75] indicated positive correlations between strength test results and the quartz contained in sandstones. The same correlation between engineering properties was observed by Petrounias et al. [25,73]. High correlations between the mechanical properties were reported in many studies [25,76,77], which took into account igneous, sedimentary and metamorphic rocks. In the present study, diabases from different ophiolite complexes, which were characterised by different genetic features and ages, were studied; they showed strongly correlated values regarding their mechanical properties, confirming and reinforcing the research gap. The relationships determined between the mechanical parameters are highly important since, in several cases, they allow for the evaluation of one property via another. As shown in Figure 9 below, a high correlation was identified between the uniaxial compressive strength (UCS) and the resistance to abrasion and attrition (LA).

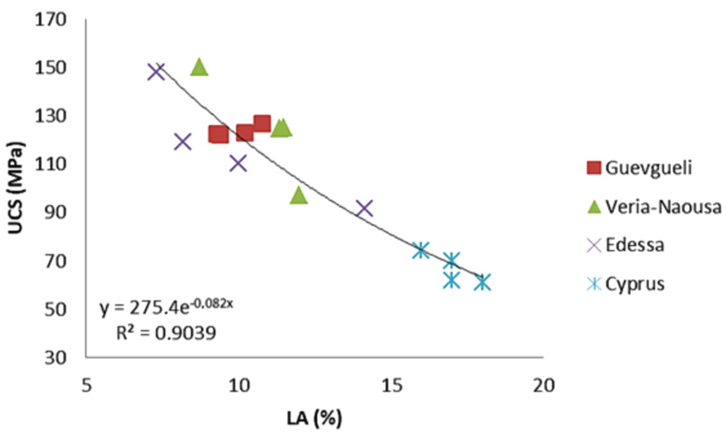

Figure 9. Uniaxial compressive strength (UCS) vs. the LA index of the investigated diabases.

As shown in Figure 9, individual grouping of the igneous rocks was evident. The diabases from Cyprus were partially grouped with most of the diabases from Edessa since they showed the lowest resistance to abrasion and attrition and the lowest uniaxial compressive strength values, while the samples from Veria-Naousa were grouped with those from the Guevgueli ophiolite complex. This range in the values of these rocks can be attributed to a combination of factors, such as the different tectonic stresses and the different grain sizes. A specific feature of the worst mechanical samples, aside from the larger grain size, was the presence of numerous crystalline microcracks and discontinuities since the discontinuities in the cylindrical specimens acted as natural slip levels during uniaxial loading, while they did not influence the smallest fragments in the abrasion and attrition. The examined rocks from Veria-Naousa and Guevgueli displayed similar microcrack patterns, where both mainly contained intragranular microcracks confined to the interior of a single grain and sparsely transgranular microcracks that crossed more than one grain. Most of them were sealed with secondary quartz and epidote. The values of the physical and mechanical parameters were strongly correlated with each other. As shown in Figure 10, the interdependence between the LA index and the moisture content (w) was conspicuous. From these diagrams, it is evident that the abrasion and attrition resistance of the lithotypes considered in the present study decreased linearly as the w values and, therefore, the n_t values increased. Similar relationships were reported by several researchers [21,78,79], enhancing the clarity of the data of this study.

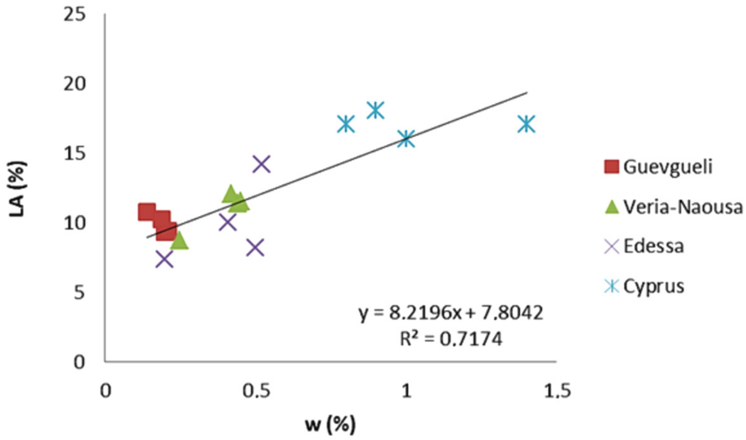

Figure 10. Moisture content (w) vs. LA index of the investigated diabases.

Figure 10 suggests that the ability of a diabase rock to retain water within its structure is positively correlated to the resistance to abrasion (LA). This fact can be interpreted physically since the pore spaces that can hold water can potentially become points of weakness during the presence of mechanical forces of friction and impact. For example, diabase rocks from Cyprus, maybe due to the early stages of rodingitization, could accommodate relatively high amounts of water in their hollow spaces, which were the main points of weakness during the loadings since the local absence of material meant that the mechanical forces were applied unevenly throughout the rock mass and expanded strongly at points of weakness, resulting in their breakdown. In addition, the presence or absence of minerals that were derived from alteration processes, such as rodingitization (which occurred in samples from Cyprus) seemed to significantly affect the correlations of engineering properties. For example, minerals such as hydrogarnet (shown in Figure 5h) can host water in their mineral structure, while at the same time, these structures exhibit the ability to act as surfaces of weakness under the presence of mechanical loads. Strong correlations were identified between the values of uniaxial compressive strength (UCS) and moisture content (w) (Figure 11). Similar correlations like those between the engineering properties were observed by Petrounias et al. [25,73].

The ability of rocks to retain water in their structure, which is related to their increased porosity properties, seemed to adversely affect the strength of rocks under uniaxial loading. The physical interpretation of these relationships is similar to the interpretation given above between the LA index and the moisture content (w). The existence of empty spaces that are capable of retaining water in their structure seemed to include all these points of possible breakage/weakness during the loading. The same mechanism was likely displayed by rocks that contained an increased percentage of secondary minerals. The above hypothesis bears the logic of the effect of the test on the specimen in question. It should be noted that during the uniaxial loading, the press forces were exerted through the flat plates on the specimens. At the next stage, especially in the case of igneous rocks due to their compact and irregular structure, the grains tended to compete with each other under loading; the stresses were evenly distributed between the grains of the rock specimens until the first point of weakness of the specimen was identified, from which the loading and breaking of the specimen followed. The existence of such individual points of weakness caused the uneven distribution of stresses and, therefore, easier breakdown of the material. Moreover, regarding the physicochemical parameters, significant correlations were identified between the soundness test (S) and the physical parameters of the aggregates. The nature of this test, which simulates the disintegration resistance of aggregates when subjected to repeated cooling–thawing cycles, is strongly correlated with the physical parameters of aggregates. The relationship between S and w is presented in Figure 12.

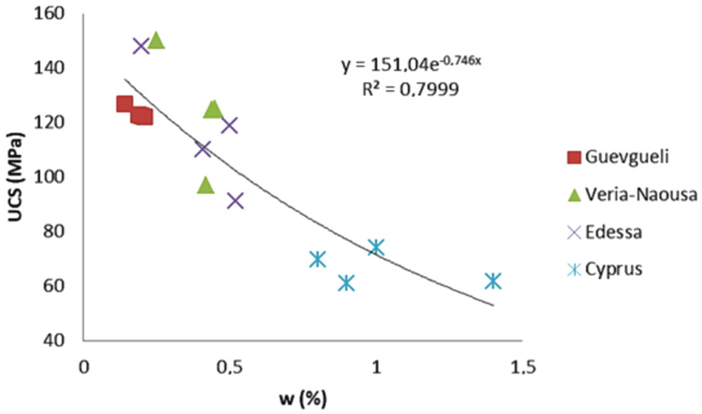

Figure 11. Moisture content (w) vs. uniaxial compressive strength (UCS) of the investigated diabases.

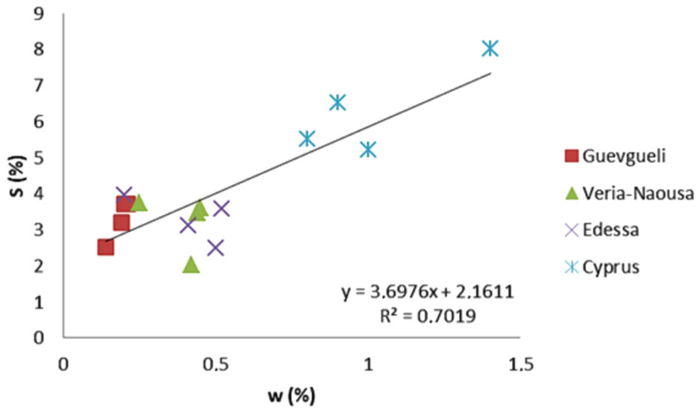

Figure 12. Moisture content (w) vs. soundness test (S) of the investigated diabases.

The above positive linear equation suggests that rocks with high porosity and high water-binding capacity in their structure are expected to be more susceptible to weathering. Furthermore, they are expected to display correlations in terms of the nature of the test since the test solution ($MgSO_4$-H_2O) penetrates the porosity of the aggregates tested during immersion and swells during drying, leading to a breakdown of rock structures and weathering. As shown in both diagrams, the altered (rodingitised) diabases derived from Cyprus and most of the diabasic samples from the Edessa ophiolite complex exhibited the highest porosities and the highest values of moisture content. They also presented less resistance in the soundness test (S) relative to the diabases derived from the Veria-Naousa and Guevgueli ophiolite complexes, which showed lower porosity values. The recommended relationships between engineering properties are close to those of Diamantis et al. [80], who examined peridotites (central Greece); Undul and Tugrul [81], who examined dunites from northwestern Turkey; and Rigopoulos et al. [21], who studied dolerites from Greece.

5.2. Evaluation of the Diabases from Different Complexes Regarding the Quality of Concrete

One of the most important factors in the final mechanical characterisation of the produced specimens was the mechanical properties of the aggregates. Either the LA index or the resistance of rocks to uniaxial compressive test (UCS) showed an interaction with the resistance of concrete to uniaxial compressive strength (UCS_{con}). The negative exponential function, which can describe the relationship between the UCS_{con} and the resistance of rocks to abrasion and attrition (LA), is given as illustrated in Figure 13. Similar trends of relationships between the mechanical properties of aggregates rocks, such as LA and UCS, and the mechanical strength of the produced concrete directly depended on the petrographic characteristics of the aggregates were proposed by several researchers when studying various types of lithotypes [19,39]. The diagram of Figure 13 shows that the aggregates with the lowest resistance to abrasion and attrition produced concrete specimens with the lowest mechanical strength. By studying the diagram of Figure 13, it is evident that there was a clear separation and grouping of the rocks, even by study area, which reinforced the view that the genetic characteristics and the final mineralogical characteristics determined the health of the rocks.

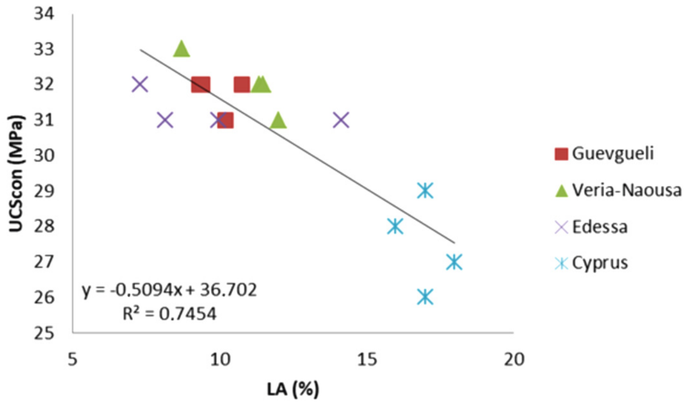

Figure 13. LA index of the investigated diabases vs. the uniaxial compressive strength of the produced concrete (UCS_{con}).

Additionally, the equation that describes the relationship between the uniaxial compressive strength of produced concrete specimens (UCS_{con}) (Figure 14) and the uniaxial compressive strength of diabases (UCS) is given by the following relation: $UCS_{con} = 6.47\ln(UCS) + 0.5583$. Similarly, the trend of the diagram in Figure 14 points out that using aggregates that were mechanically weak resulted in the production of low-quality concrete, which is something that may have happened due to the secondary phyllosilicate minerals contained since these minerals may have formed slide surfaces [19].

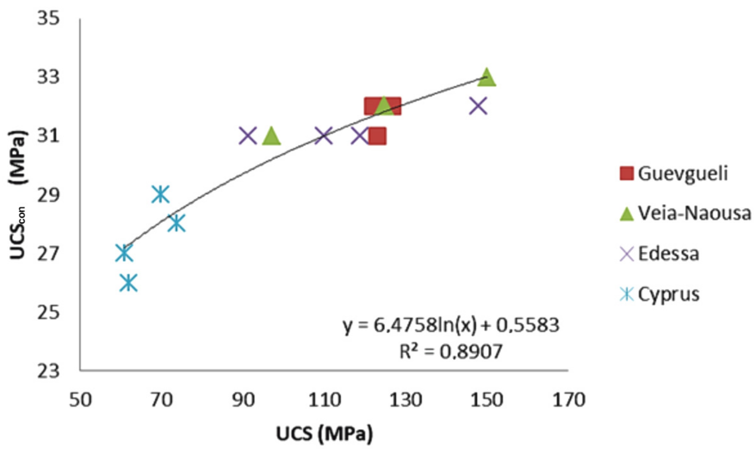

Figure 14. Uniaxial compressive strength of the investigated diabases (UCS) vs. the uniaxial compressive strength of the produced concrete specimens (UCS_{con}).

All the above correlations between the mechanical properties of the aggregates and the concrete strength indicated that the diabases of lower mechanical strength produced concrete of lower strength. The above-stated view was supported by the numerous microcracks that were found penetrating both the cement paste and the fragments of low strength during the petrographic study of the concrete (Figure 8g,h). These fragments tended to break due to their low mechanical strength at the same time as the cement paste without showing mechanical resistance, exactly as in the case with the samples from Cyprus and some from Edessa.

Moreover, some structural characteristics of the aggregates may influence both the mechanical properties of the aggregates and the mechanical strength of the produced concrete. For example, the structural characteristics of the rodingitised diabases from Cyprus that displayed granoblastic garnet segregations seemed to determine to a significant extent the mechanical properties of diabases used as aggregates and their concrete strength. As shown through the microscopic observations of the concrete thin sections, the hydrogarnet displaying isomorphic mixtures between grossular and andradite exhibited venous and cloudy textures. Thus, it was possible for them to be separated to a large degree during the loading of the cylindrical specimen while conducting the uniaxial compressive strength test. In contrast, the concrete specimens prepared from diabases from the Veria-Naousa and Guevgueli ophiolite complexes did not seem to present systematic extensive microscopic failures due to their higher strength compared with those derived from the Cyprus and Edessa ophiolite complexes, as shown in Figure 14.

In general, the presence of secondary minerals in the diabase rocks seemed to have a negative effect on the concrete strength. This was due, on the one hand, to the ability of these minerals to adsorb water (which is necessary for the hardening of the cement) and, on the other hand, to the fact that these minerals had much lower mechanical strength than the primary ones where they were replaced. The negative impact of other phyllosilicate minerals on concrete was considered by research studies [19,25]. Based on all the above results, it became clear that as the percentages of secondary minerals in the mineralogical composition of the aggregates used increased, so did the strength of the concrete produced in which these aggregates were used.

In addition, all the above regarding the interaction of aggregates and mortar was confirmed by the correlation between the final concrete strength (UCS_{con}) and the soundness test (S) (Figure 15). This correlation showed that the samples that had low resistance to alternations of cooling and heating cycles, such as the samples from Cyprus also had a low final concrete strength, which was due to the ability of the aggregates to absorb water in their structure. The diabases with a high capacity for water adsorption and, therefore, for the $MgCO_3$ solution showed faster breaking of their structure and, therefore, low soundness test values. The same samples with their increased ability to adsorb water showed that when they were inside the mortars, they absorbed an increased amount of water, which was necessary for the hardening of the cement. Therefore, the concrete showed a series of imperfect hydration reactions of the cement and low concrete strength.

As can be observed from all the above correlations, the effects of the mineralogy and special micropetrographic characteristics of the diabase aggregate rocks played significant roles in the final mechanical performance of the concrete specimens, as they determined the cohesion between the used aggregates and the cement paste. More specifically, as can be seen in Figure 8, the diabase samples derived from the Veria-Naousa and Guevgueli ophiolite complexes presented considerably better cohesion between the cement paste and the aggregates (Figure 8a,b,e,f) than those derived from the Troodos ophiolite complex, which displayed the majority of failures and microcracks among all the produced specimens, triggering defects and weaknesses in it. The presence of the early stages of rodingitisation in the diabase samples of Troodos, which were observed for the first time, led to the frequency of the referred failures and microcracks in the produced concrete specimens.

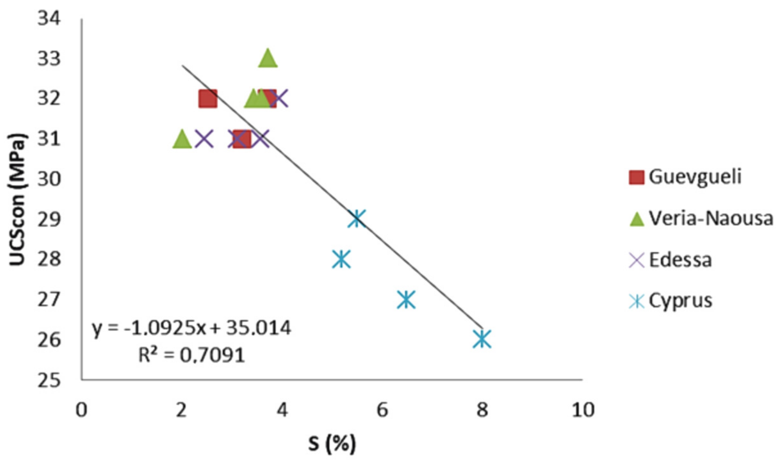

Figure 15. Soundness test (S) of the investigated diabases vs. the uniaxial compressive strength (UCS_{con}) of the investigated concrete specimens.

5.3. The Impact of the Microroughness of the Aggregates on the Final Mechanical Behaviour of the Produced Concrete

The surface texture of the aggregate grains, as determined using the secondary electron images (SEI) (Figure 7), significantly determined the bonding of the aggregates with the cement paste and hence the resistance of the concrete on the mechanical loading [15,39,41]. It is quite difficult to safely quantify the surface texture of the aggregate grains, as well as correlate it directly with the concrete strength. However, in the present study, for the first time, a three-dimensional (3D) processing of representative images of thin sections of concrete specimens containing diabases from different complexes of Greece and Cyprus was performed to present the effects of surface texture on the bonding of aggregates with the cement paste (Figure 16). The following figures are real 3D illustrations of the surface texture of the concrete, as they were captured in each thin section after grinding and polishing during the preparation process (Figure 16).

As mentioned, the diabases from Cyprus and some from the Edessa ophiolite complex tended to show lower microtopography compared with all the other examined diabases due to the flat surfaces created by chlorite and garnet. As shown in Figure 16g,h, garnet (produced through rodingitisation) seemed to create flat surfaces that produced lower microtopography, even from the cement paste (cement-carbonated sand). In these extended flat surfaces, it was not possible to perform satisfactory bonding between the cement paste and the aggregate particles, leading to the formation of points of weakness in the concrete. On the other hand, the diabase rocks from the Veria-Naousa and Guevgueli ophiolite complexes showed in their entirety an increased microroughness, which tended to create juxtaposed formations (Figure 16a,b,e,f). These formations also created a satisfactory substrate for the adhesion of the cement paste, increasing the mechanical endurance of the produced concrete.

This occurred because the aggregate (diabase) acted as a container of the cement paste around it by accepting the penetration of the cement paste during its initial maturation between the protruding mineral phases. As a result, the cement paste, when fully cured, also acquired a small relief on the interface between the cement paste and the aggregate. A typical example of a sample of increased microroughness is sample BE.43, which, as shown in Figure 16b, displayed a higher microtopography than that of the cement paste, creating juxtaposed formations. The diabases that contained small percentages of evenly distributed chlorite were of great interest. This happened because they showed increased microroughness as a result of the combination of smooth and flat surfaces of chlorite and other mineral phases, such as pyroxene and plagioclase. The positive effect of alteration on the maintenance of microroughness was reported by many researchers [19,29,82]. As shown in the aforementioned figures, the existence of evenly distributed chlorite had a positive effect on all the concrete specimens produced by diabases from the Veria-Naousa and Guevgueli ophiolite complexes. As the points where chlorite pre-existed accounted for the reception points of the cement paste, this led to the creation of a high interaction between the aggregates and the cement. The albite penetrations into the diabase rocks also had a positive effect since they produced local outbursts of the microtopography.

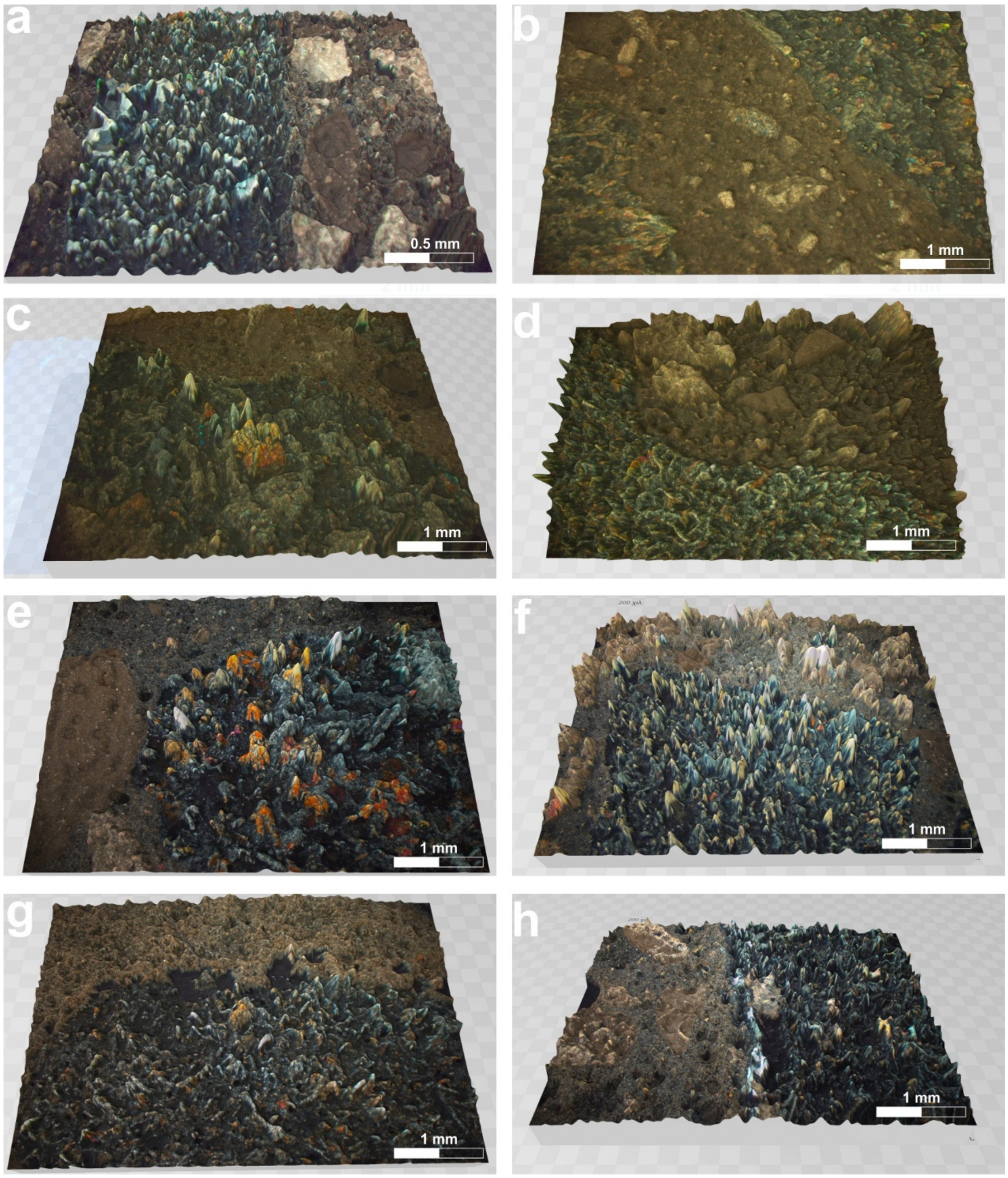

Figure 16. Three-dimensional depictions of the investigated concrete specimens derived from all the studied ophiolite complexes. (**a**,**b**) Concretes that contained diabase aggregates derived from the Veria-Naousa ophiolite complex. (**c**,**d**) Concretes that contained diabase aggregates derived from the Edessa ophiolite complex. (**e**,**f**) Concretes that contained diabase aggregates derived from the Guevgueli ophiolite complex. (**g**,**h**) Concretes that contained diabase aggregates derived from the Troodos ophiolite complex.

The statistical accuracy of the above data was rechecked using a *t*-test and given using the *p*-value. The significantly higher values of the *t*-test than the critical t-table, the *p*-value of these pairs much lower than the typical 0.05 and confidence levels even higher than 99% strongly indicated the validity of the aforementioned relations (Table 5). These statistical accuracies of similar relationships were shown using the *t*-test analysis (i.e., [23,82]), enhancing the strong relationship either between the engineering properties or between them and the mechanical behaviour of the produced concrete.

Table 5. Paired *t*-test results for the statistical correlations of the samples and the concrete correlations. The given critical t-table values were for the relevant freedom degrees (dF) and confidence levels of 99% (α = 0.01), 98% (α = 0.02), 95% (α = 0.05) and 90% (α = 0.10).

Pair	*t*-Test	dF	*p*-Value	t-Table Values				Figure
				α = 0.01	α = 0.02	α = 0.05	α = 0.10	
LA–UCS	−12.015149	15	0.0000000042488	2.947	2.602	2.131	1.753	9
W–LA	−14.537938	15	0.00000000030169	2.947	2.602	2.131	1.753	10
W–UCS	−14.81061	15	0.00000000023224	2.947	2.602	2.131	1.753	11
W–S	−10.9701	15	0.000000014586	2.947	2.602	2.131	1.753	12
LA–UCScon	−14.135563	15	0.0000000004474	2.947	2.602	2.131	1.753	13
UCS–UCScon	11.510811	15	0.0000000076185	2.947	2.602	2.131	1.753	14
S–UCScon	−30.845358	15	0.000000000000005515	2.947	2.602	2.131	1.753	15

6. Conclusions

This study considered diabases from various ophiolite complexes from both Greece (Veria-Naousa, Edessa and Guevgueli) and Cyprus (Troodos) to evaluate their suitability as concrete aggregates. The basic conclusions of the study are given below:

- The intense high strength and durability of the altered diabases result from the low amount of soft minerals and microcracks, along with the preservation of igneous textures.
- Diabases from the Veria-Naousa and Guevgueli ophiolite complexes showed better engineering properties in contrast to those derived from the Edesssa ophiolite complex and even more than those derived from Cyprus (Troodos ophiolite complex), which strongly depended on their alteration degree.
- The microstructural characteristics of the diabases seemed to be the critical parameter for the mechanical behaviour of the produced concrete specimens, where those made using Veria-Naousas' and Guevguelis' diabases were classified as the most durable ones; in contrast, those made using Edessas' and Cyprus' diabases were of lower quality.
- The mechanical performance of the produced concrete specimens was directly dependent on the micropetrographic characteristics of the concrete aggregates.
- The decisive factors for achieving better bonding between the cement paste and the aggregate in the concrete (optimum cohesion) were the microstructural characteristics of the aggregates contained, enhancing the contribution of petrography in engineering geology.
- Petrography may act as a useful tool in order to predict the mechanical behaviour of aggregate rocks and the produced concrete specimens.

Author Contributions: Conceptualisation, P.P., P.P.G. and A.R.; methodology, P.P., P.P.G., A.R., A.P., P.L., P.K. and V.G.; software, P.L., N.K. and V.G.; validation, P.P., P.P.G., A.R. and A.P.; formal analysis, P.P., P.P.G., A.R. and A.P.; investigation, P.P., P.P.G., A.R., A.P. and K.H.; resources, P.P., P.P.G., A.R., A.P., V.G., P.L. and P.K.; data curation, P.P., P.P.G., A.R., A.P., V.G., P.L. and P.K.; writing—original draft preparation, P.P., P.P.G., A.R. and A.P.; writing—review and editing, P.P., P.P.G. and A.R.; visualisation, P.P.; supervision, P.P., P.P.G., A.R. and K.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: We kindly thank B. Tsikouras for his assistance in the fieldwork, in the interpretation of the results and for his overall contribution to this study. We also thank M. Kalpogiannaki for her assistance in the construction of the geological maps. We also thank I. Iliopoulos for his assistance during the whole research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ghannam, S.; Najm, H.; Vasconez, R. Experimental study of concrete made with granite and iron powders as partial replacement of sand. *Sustain. Mater. Technol.* **2016**, *9*, 1–9. [CrossRef]
2. Singh, M.; Choudhary, K.; Srivastava, A.; Sangwan, K.S.; Bhunia, D. A study on environmental and economic impacts of using waste marble powder in concrete. *J. Build. Eng.* **2017**, *13*, 87–95. [CrossRef]
3. Amudhavalli, N.; Sivasankar, S.; Shunmugasundaram, M.; Kumar, A.P. Characteristics of granite dust concrete with M-sand as replacement of fine aggregate composites. *Mater. Today* **2020**, *27*, 1401–1406. [CrossRef]
4. Ahmadi, S.F.; Reisi, M.; Amiri, M.C. Reusing granite waste in eco-friendly foamed concrete as aggregate. *J. Build. Eng.* **2022**, *46*, 103566. [CrossRef]
5. Radonjanin, V.; Malešev, M.; Marinković, S.; Al Malty, A.E.S. Green recycled aggregate concrete. *Construct. Build. Mater.* **2013**, *47*, 1503–1511. [CrossRef]
6. Çakır, O. Experimental analysis of properties of recycled coarse aggregate (RCA) concrete with mineral additives. *Construct. Build. Mater.* **2014**, *68*, 17–25. [CrossRef]
7. Pacheco-Torgal, F. Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. *Construct. Build. Mater.* **2014**, *51*, 151–162. [CrossRef]
8. Marie, I.; Quiasrawi, H. Closed-loop recycling of recycled concrete aggregates. *J. Clean. Prod.* **2012**, *37*, 243–248. [CrossRef]
9. Yaragal, S.C.; Basavana Gowda, S.N.; Rajasekaran, C. Characterization and performance of processed lateritic fine aggregates in cement mortars and concretes. *Construct. Build. Mater.* **2019**, *200*, 10–25. [CrossRef]
10. Behera, M.; Bhattacharyya, S.K.; Minocha, A.K.; Deoliya, R.; Maiti, S. Recycled aggregate from C&D waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review. *Construct. Build. Mater.* **2014**, *68*, 501–516.
11. Magbool, H.M. Utilisation of ceramic waste aggregate and its effect on Eco-friendly concrete: A review. *J. Build. Eng.* **2022**, *47*, 103815. [CrossRef]
12. Jackson, N. *Civil Engineering Materials*; Macmillan Press Ltd.: London, UK, 1981.
13. Taylor, G.D. *Materials in Construction*, 2nd ed.; Longman Group Ltd., Longman House, Burnt Mill: Harlow, UK, 1994.
14. Rajput, R.K. *Engineering Materials*, 3rd ed.; S. Chard & Company Ltd.: New Delhi, India, 2006.
15. Neville, A.M. *Properties of Concrete*, 4th ed.; Pitman: London, UK, 1995.
16. Aulia, T.B.; Deutschmann, K. Effect of mechanical properties of aggregate on the ductility of high performance concrete. *Lacer* **1999**, *4*, 133–147.
17. Thomas, M.D.A.; Folliard, K.J. Concrete aggregates and the durability of concrete. *Durab. Concr. Cem. Compos.* **2007**, *10*, 247–281.
18. Yilmaz, M.; Turgul, A. The effects of different sandstone aggregates on concrete strength. *Constr. Build. Mater.* **2012**, *35*, 294–303. [CrossRef]
19. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Stamatis, P.M.; Tsikouras, B.; Papoulis, D.; Lampropoulou, P.; Hatzipanagiotou, K. The influence of alteration of aggregates on the quality of the concrete: A case study from serpentinites and andesites from central Macedonia (North Greece). *Geosciences* **2018**, *8*, 115. [CrossRef]
20. Al-Oraimi, S.K.; Taha, R.; Hassan, H.F. The effect of the mineralogy of coarse aggregate on the mechanical properties of high-strength concrete. *Constr. Build. Mater.* **2006**, *20*, 499–503. [CrossRef]
21. Rigopoulos, I.; Tsikouras, B.; Pomonis, P.; Hatzipanagiotou, K. The influence of alteration on the engineering properties of diabases: The example from the Pindos and Vourinos ophiolites (northern Greece). *Int. J. Rock Mech. Min. Sci.* **2010**, *47*, 69–80. [CrossRef]
22. Yilmaz, N.G.; Goktan, R.M.; Kibici, Y. Relations between some quantitative petrographic characteristics and mechanical strength properties of granitic building stones. *Int. J. Rock Mech. Min. Sci.* **2011**, *48*, 506–513. [CrossRef]
23. Petrounias, P.; Rogkala, A.; Kalpogiannaki, M.; Tsikouras, B.; Hatzipanagiotou, K. Comparative study of physico-mechanical properties of ultrabasic rocks (Veria-Naousa ophiolite) and andesites from central Macedonia (Greece). *Bull. Geol. Soc. Gr.* **2016**, *50*, 1989–1998.
24. Giannakopoulou, P.P.; Tsikouras, B.; Hatzipanagiotou, K. The interdependence of mechanical properties of ultramafic rocks from Geraniaophiolitic complex. *Bull. Geol. Soc. Gr.* **2016**, *50*, 1829–1837.
25. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Lampropoulou, P.; Koutsopoulou, E.; Papoulis, D.; Tsikouras, B.; Hatzipanagiotou, K. The Impact of Secondary Phyllosilicate Minerals on the Engineering Properties of Various Igneous Aggregates from Greece. *Minerals* **2018**, *8*, 329. [CrossRef]
26. Shakoor, A.; Bonelli, R.E. Relationship between petrographic characteristics, engineering index properties and mechanical properties of selected sandstones. *Bull. Ass. Eng. Geol.* **1991**, *28*, 55–71. [CrossRef]
27. Haney, M.G.; Dhakoor, A. The relationship between tensile and compressive strengths for selected sandstones as influenced by index properties and petrographic characteristics. In Proceedings of the 7th International IAEG Congress, Lisbon, Portugal, 5–9 September 1996; Volume IV, pp. 3013–3021.
28. Turgul, A.; Zarif, I. Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. *Eng. Geol.* **1999**, *51*, 303–317.
29. Smith, M.R.; Collis, L. *Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes*; The Geological Society: London, UK, 2001.

30. Miskovsky, K.; Tabora, D.M.; Kou, S.Q.; Lindqvist, P.A. Influence of the mineralogical compositionand textural properties on the quality of coarse aggregates. *J. Mater. Eng. Perform.* **2004**, *13*, 144–150. [CrossRef]
31. LaLonde, W.S.; Janes, M.F. *Concrete Engineering Handbook*; Library of Congress: New York, NY, USA, 1961.
32. Dawood, E.T.; Ramli, M. Contribution of Hybrid Fibers on The Hybrid Fibers on the Properties of High Strength Concrete Having High Workability. *Procedia* **2011**, *14*, 814–820. [CrossRef]
33. Mishuk, B.; Rahman, A.M.; Ashrafuzzaman, M.; Barua, S. Effect of Aggregates Properties on the Crushed Strength of Aggregates. *Int. J. Mater. Sci. Appl.* **2015**, *4*, 343–349.
34. Nevile, A.M. *Properties of Concrete*; Longman: London, UK, 2011.
35. Buertey, J.T.; Atsrim, F.; Ofei, W.S. An Examination of the Physiomechanical Properties of Rock Lump and Aggregates in Three Leading Quarry Sites near Accra. *Am. J. Civ. Eng.* **2016**, *4*, 264–275. [CrossRef]
36. Gonilho Pereira, C.; Castro-Gomes, J.; Pereira de Oliveira, L. Influence of natural coarse aggregate size, mineralogy and water content on the permeability of structural concrete. *Constr. Build. Mater.* **2009**, *23*, 602–608. [CrossRef]
37. Kiliç, A.; Atiş, C.D.; Teymen, A.; Karahan, O.; Özcan, F.; Bilim, C.; Özdemir, M. The influence of aggregate type on the strength and abrasion resistance of high strength concrete. *Cement Concr. Comp.* **2008**, *30*, 290–296. [CrossRef]
38. Piasta, W.; Góra, J.; Turkiewicz, T. Properties and durability of coarse igneous rock aggregates and concretes. *Constr. Build. Mater.* **2016**, *126*, 119–129. [CrossRef]
39. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Kalpogiannaki, M.; Koutsovitis, P.; Damoulianou, M.-E.; Koukouzas, N. Petrographic Characteristics of Sandstones as a Basis to Evaluate Their Suitability in Construction and Energy Storage Applications. A Case Study from KlepaNafpaktias (Central Western Greece). *Energies* **2020**, *13*, 1119. [CrossRef]
40. Özturan, T.; Çeçen, C. Effect of coarse aggregate type on mechanical properties of concretes with different strengths. *Cem. Concr.* **2007**, *27*, 165–170. [CrossRef]
41. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Stamatis, P.M.; Lampropoulou, P.; Tsikouras, B.; Hatzipanagiotou, K. The Effect of Petrographic Characteristics and Physico-Mechanical Properties of Aggregates on the Quality of Concrete. *Minerals* **2018**, *8*, 577. [CrossRef]
42. Rogkala, A.; Petrounias, P.; Tsikouras, B.; Hatzipanagiotou, K. New Occurrence of Pyroxenites in the Veria-NaousaOphiolite (North Greece): Implications on Their Origin and Petrogenetic Evolution. *Geosciences* **2017**, *7*, 92. [CrossRef]
43. Rogkala, A.; Petrounias, P.; Tsikouras, B.; Hatzipanagiotou, K. Petrogenetic significance of spinel from serpentinised peridotites from Veria-Naousa ophiolite. *Bull. Geol. Soc. Gr.* **2016**, *50*, 1999–2008.
44. Rogkala, A.; Petrounias, P.; Koutsovitis, P.; Giannakopoulou, P.P.; Pomonis, P.; Lampropoulou, P.; Hatzipanagiotou, K. Rodingites from the Veria-Naousa ophiolite (Greece): Mineralogical evolution, metasomatism and petrogenetic processes. *Geochemistry* **2022**, *82*, 125860. [CrossRef]
45. Brunn, J.H. *Geological Map of Greece, Veroia Sheet, 1:50.000*; IGME: Athens, Greece, 1982.
46. Decourt, J.; Aubouin, J.; Savoyat, E. Le sill on méso hellénique et la zone pélagonienne. *Bull. Soc. Géol. Fr.* **1977**, *1*, 32–70.
47. Michailidis, K.M. Zoned chromites with high Mn-contents in the Fe-Ni-Cr-laterite ore deposits from the Edessa area in Northern Greece. *Miner. Depos.* **1990**, *25*, 190–197. [CrossRef]
48. Pe-Piper, G.; Piper, D.J.W. *The Igneous Rocks of Greece: The Anatomy of an Orogen*; Gebrueder Borntraeger: Berlin/Stuttgart, Germany, 2002.
49. Rogkala, A.; Petrounias, P.; Tsikouras, B.; Giannakopoulou, P.P.; Hatzipanagiotou, K. Mineralogical Evidence for Partial Melting and Melt-Rock Interaction Processes in the Mantle Peridotites of Edessa Ophiolite (North Greece). *Minerals* **2019**, *9*, 120. [CrossRef]
50. Eleftheriadis, G.; Castorina, F.; Soldatos, T.; Masi, U. Geochemical and Sr-Nd isotopic evidence for the genesis of the Late Cainozoic Almopia volcanic rocks (Central Macedonia, Greece). *Mineral. Petrol.* **2003**, *78*, 21–36. [CrossRef]
51. Mercier, J.L.; Vergely, P. *Geological Map of Greece, Edhessa Sheet, 1:50.000*; IGME: Athens, Greece, 1984.
52. Saccani, E.; Bortolotti, V.; Marroni, M.; Pandolfi, L.; Photiades, A.; Principi, G. The Jurassic association of backarc basin ophiolites and calc-alkaline volcanics in the Guevgueli complex (Northern Greece): Implication for the evolution of the Vardar zone. *Ofioliti* **2008**, *33*, 209–227.
53. Zachariadis, P.; Kostopoulos, D.; Reischmann, T.; Himmerkus, F.; Matukov, D.; Sergeev, S. U-Pb ion-microprobe zircon dating of subduction-related magmatism from northern Greece: The ages of the Guevgueli, Thessaloniki and Chalkidiki igneous complexes. *Geophys. Res.* **2006**, *Abstr 8*, 055560.
54. Mavrides, A.; Matarangas, D.; Karfakis, J. *Geological Map of Greece, Skra Sheet, 1:50.000*; IGME: Athens, Greece, 1982.
55. Mercier, J.L.; Kougoulis, C. *Geological Map of Greece, Evzoni Sheet, 1:50.000*; IGME: Athens, Greece, 1987.
56. Urquhart, E.; Banner, F.T. Biostratigraphy of the supra-ophiolite sediments of the Troodos Massif, Cyprus: The Cretaceous Perapedhi, Kannaviou, Moni and Kathikas formations. *Geol. Magaz.* **1994**, *131*, 499–518. [CrossRef]
57. *AASHTO T255*; Standard Method of Test for Total Evaporable Moisture Content of Aggregate by Drying. ASTM International:: West Conshohocken, PA, USA, 2000.
58. ISRM. Suggested Methods. In *Rock Characterization Testing and Monitoring*; Brown, E., Ed.; Pergamon Press: Oxford, UK, 1981.
59. *BS 812*; Testing Aggregates, Part 105: Methods for Determination of Particle Shape. Section: 105.1: Flakiness Index. British Standards Institution: London, UK, 1989.
60. *BS 812*; Testing Aggregates, Part 105: Methods for Determination of Particle Shape. Section: 105.2: Elongation Index. British Standards Institution: London, UK, 1990.

61. *ASTM C-131*; Resistance to Abrasion of Small-Size Coarse Aggregate by Use of the Los Angeles Machine. ASTM: Philadelphia, PA, USA, 1989.
62. *ASTM D 2938-95*; Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens. American Society for Testing and Materials: West Conshohocken, PA, USA, 2002.
63. *EN 1367-2*; Tests for Thermal and Weathering Properties of Aggregates—Part 2: Magnesium Sulfate Test. European Committee for Standardization: Brussels, Belgium, 1999.
64. *EN 932*; Part 3: Procedure and Terminology for Simplified Petrographic Description. European Standard: Warsaw, Poland, 1996.
65. Bish, D.L.; Post, J.E. Quantitative mineralogical analysis using the Rietveld full- pattern fitting method. *Am. Mineral.* **1993**, *78*, 932–940.
66. *BS 812*; Methods for Sampling and Testing of Mineral Aggregates, Sands and Fillers, Part 1: Methods for Determination of Particle Size and Shape. British Standard Institution: London, UK, 1975.
67. *ACI-2111-91*; Standard for Selecting Proportions for Normal, Heavyweight and Mass Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2002.
68. *BS EN 12390*; Part 3: Testing Hardened Concrete. Compressive Strength of Test Specimens. British Standard Institution: London, UK, 2009.
69. *ASTM C856*; Standard Practice for Petrographic Examination of Hardened Concrete. American Society for Testing and Materials: West Conshohocken, PA, USA, 2017.
70. Farzadnia, N.; Abang, A.A.A.; Demirboga, R.; Anwar, M.P. Effect of halloysite nano clay on mechanical properties, thermal behavior and microstructure of cement mortars. *Cem. Concr. Res.* **2013**, *48*, 97–104. [CrossRef]
71. Golewski, G.L. An assessment of microcracks in the interfacial transition zone of durable concrete composites with fly additives. *Compos. Struct.* **2018**, *200*, 515–520. [CrossRef]
72. Meng, Y.; Ling, T.G.; Mo, K.H. Recycling of wastes for value-added applications in concrete blocks: An overview. *Resour. Conserv. Recycl.* **2018**, *138*, 298–312. [CrossRef]
73. Petrounias, P.; Giannakopoulou, P.P.; Rogkala, A.; Lampropoulou, P.; Tsikouras, B.; Rigopoulos, I.; Hatzipanagiotou, K. Petrographic and Mechanical Characteristics of Concrete Produced by Different Type of Recycled Materials. *Geosciences* **2019**, *9*, 264. [CrossRef]
74. Petrounias, P.; Rogkala, A.; Giannakopoulou, P.P.; Christogerou, A.; Lampropoulou, P.; Liogris, S.; Koutsovitis, P.; Koukouzas, N. Utilization of Industrial Ferronickel Slags as Recycled Concrete Aggregates. *Appl. Sci.* **2022**, *12*, 2231. [CrossRef]
75. Gunsallus, K.L.; Kulhawy, F.H. A comparative evaluation of rock strength measures. *Int. J. Rock Mech. Min. Sci.* **1984**, *21*, 233–248. [CrossRef]
76. Kahraman, S.; Fener, M. Predicting the Los Angeles abrasion loss of rock aggregates from the uniaxial compressive strength. *Mat. Lett.* **2007**, *61*, 4865–4891. [CrossRef]
77. Ugur, I.; Demirdag, S.; Yavuz, H. Effect of rock properties on the Los Angeles abrasion and impact test characteristics of the aggregates. *Mat. Charact.* **2010**, *61*, 90–96. [CrossRef]
78. Koukis, G.; Sabatakakis, N.; Spyropoulos, A. Resistance variation of low-quality aggregates. *Bull. Eng. Geol. Environ.* **2007**, *66*, 457–466. [CrossRef]
79. Giannakopoulou, P.P.; Petrounias, P.; Tsikouras, B.; Kalaitzidis, S.; Rogkala, A.; Hatzipanagiotou, K.; Tombros, S.F. Using Factor Analysis to Determine the Interrelationships between the Engineering Properties of Aggregates from Igneous Rocks in Greece. *Minerals* **2018**, *8*, 580. [CrossRef]
80. Diamantis, K.; Gartzos, E.; Migiros, G. Study on uniaxial compressive strength, point load strength index, dynamic and physical properties of serpentinites from Central Greece: Test results and empirical relations. *Eng. Geol.* **2009**, *108*, 199–207. [CrossRef]
81. Undul, O.; Tugrul, A. On the variations of geo-engineering properties of dunites and diorites related to weathering. *Environ. Earth Sci.* **2016**, *75*, 1326. [CrossRef]
82. Giannakopoulou, P.P.; Petrounias, P.; Rogkala, A.; Tsikouras, B.; Stamatis, P.M.; Pomonis, P.; Hatzipanagiotou, K. The Influence of the Mineralogical Composition of Ultramafic Rocks on Their Engineering Performance: A Case Study from the Veria-Naousa and GeraniaOphiolite Complexes (Greece). *Geosciences* **2018**, *8*, 251. [CrossRef]