Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi
Pamukkale University Journal of Engineering Sciences

The production of phenolic resin-based abrasive with use of solid waste sand of foundry industry

Döküm endüstrisi katı atık kumu kullanımı ile fenolik reçine bazlı aşındırıcı üretimi

Tuba Bahtlı[1], Yasin Ramazan Eker[2], Veysel Murat Bostancı[3], Pınar Uyan[4]*

[1]Department of Metallurgical and Materials Engineering, Faculty of Engineering, Necmettin Erbakan University, Konya, Türkiye.
taksoy@erbakan.edu.tr
[2]Department of Basic Sciences, Faculty of Engineering, Necmettin Erbakan University, Konya, Türkiye.
yeker@erbakan.edu.tr
[3]Science and Technology Research and Application Center, Faculty of Engineering, Necmettin Erbakan University, Konya, Türkiye.
veyselmurat.bostanci@erbakan.edu.tr
[4]Department of Machinery and Metal Technologies, Vocational School, Bilecik Seyh Edebali University, Bilecik, Türkiye.
pinar.uyan@bilecik.edu.tr

Received/Geliş Tarihi: 29.01.2025 Revision/Düzeltme Tarihi: 26.09.2025 doi: 10.65206/pajes.00579
Accepted/Kabul Tarihi: 22.10.2025 Research Article/Araştırma Makalesi

Abstract

Molding sand, which becomes solid waste after casting processes, is an important item to be recycled and used, as well as turning it into useful products with economic value, due to the fact that it creates an environmental problem and increases storage costs. The studies on this subject are still insufficient. In this study, the SiC phase were obtained from solid waste casting sand whose basic material is silica and from phenolic resin as a C source, and their usability as an abrasive was investigated. Densities of the products were measured with a Helium pycnometer; the hardness with a Shore D device; pore structure and distribution with the BET method; the surface functions with a FTIR Fourier Transform Infrared Spectrometer; the development of bonds in the structure and morphology with a Confocal Raman Microscope; the phase analysis using the XRD method; and microstructural examinations with SEM analysis. As a result, it was determined that a high temperature was needed to obtain the SiC phase with the conventional pressure less sintering method using solid waste casting sand, but the resin used did not withstand the required high temperature.

Keywords: SiC, abrasive, phenolic resin, waste recovery, foundry sand.

Öz

Döküm işlemlerinden sonra katı atık haline gelen kalıp kumu, çevresel bir sorun yaratması ve depolama maliyetlerini artırması nedeniyle geri dönüştürülerek kullanılması ve ekonomik değeri olan faydalı ürünlere dönüştürülmesi önemli bir maddedir. Bu konuda yapılan çalışmalar henüz yetersizdir. Bu çalışmada, temel malzemesi silika olan katı atık döküm kumu ve C kaynağı olarak fenolik reçineden SiC fazı elde edilmiş ve aşındırıcı olarak kullanılabilirlikleri araştırılmıştır. Üretilen ürünlerin yoğunlukları Helyum piknometresi ile; sertlik değeri Shore D cihazı ile; gözenek yapısı ve dağılımı BET yöntemi ile; yüzey fonksiyonları FTIR Fourier Dönüşümlü Kızılötesi Spektrometresi ile; yapı ve morfolojideki bağların gelişimi Konfokal Raman Mikroskobu ile; faz analizi XRD yöntemi ile; mikroyapısal incelemeler SEM analizi ile yapılmıştır. Sonuç olarak, katı atık döküm kumu kullanılarak yapılan konvansiyonel basınçsız sinterleme yöntemi ile SiC fazının elde edilmesi için yüksek sıcaklığa ihtiyaç duyulduğu, ancak kullanılan reçinenin gerekli yüksek sıcaklığa dayanamadığı belirlenmiştir.

Anahtar Kelimeler: SiC, aşındırıcı, fenolik reçine, atık geri kazanımı, döküm kumu.

1 Introduction

Casting is the manufacturing method used to obtain the desired shape of a part by pouring molten metal alloys into the cavity of a mold prepared for the part to be produced and solidifying it after cooling [1]. The iron-casting industry is an industry in which raw iron, steel scrap, and ferro-alloys are melted in furnaces such as induction furnaces, arc furnaces, or cupola furnaces, then poured into sand, ceramic or metal molds and shaped, producing products such as steel, gray cast iron, spheroidal cast iron and malleable cast iron needed by the industry [2].

Literature includes new applications using advanced materials in casting technologies. For example; Bolat et al. (2022) studied about Al 7075/bubble alumina syntactic foams that were fabricated by recyclable pressure infiltration casting method. They found that foam density increased, foams had higher compression strength compression strength due to higher heat treatment [3]. Bolat et al. (2021) produced pumice filled aluminum syntactic foams by a fully automated cold chamber die casting technique. As the pumice particle size increased, the average compressive strength and densities of foams decreased in this study [4].

Kumar et al. fabricated Al7150 alloys-based hybrid nanocomposite incorporating boron carbide and graphene nanoparticles by double ultrasonic two-stage stir casting method. They indicated that nano reinforcements improved the mechanical properties of the hybrid nanocomposite because of enhanced interfacial bonding and dislocation strengthening [5].

Lai et al. studied in order to develop porous dual-scale 316L stainless steel by incorporating the 3D-printed templates used to offer macro-scale gyroscopic channels into anisotropic

*Corresponding author/Yazışılan Yazar

micro-scale lamellar porous structures through the freeze-casting process. They successfully built macro-scale gyroid channels into the micro-scale open-cellular lamellar porous scaffolds [6].

The casting methods can be divided into two groups according to whether the mold materials used can be reused or not, as methods use consumable (non-permanent) and non-consumable (permanent) molds. The methods using non-permanent molds are primarily traditional sand mold casting, shell mold casting, ceramic mold casting, plaster mold casting, and precision casting. The casting methods using permanent molds are permanent mold casting, pressure casting, centrifugal casting, and continuous casting. The casting method to be selected in manufacturing by casting varies according to the type of alloy to be cast, part size, and production cost, and the limitations of each casting method necessitate manufacturing with another casting method. The most commonly used, economical, and economical method, where parts of different sizes can be cast, is the sand mold casting method, in which silica sand grains are bonded with an optimum amount of water and clay as a binder. The model is placed in a degree, and the mold is prepared by compacting the surrounding area with sand. When the model is removed, the mold cavity is formed. When the liquid metal is poured, it fills a mold cavity and solidifies. The sand mold is broken, but the casting part is removed and cleaned. The main reasons why silica sand is preferred in foundries are that it is easy to find, has low cost, and has refractory properties that can withstand and absorb molten metal interactions [7, 8].

The molding sands are broken down after the casting process, and the large particles in the sand are sieved and removed; the process continues by adding new sand to the amount the original sand has decreased [9, 10]. Ultimately, the sand used in casting becomes unusable for molding more than a certain number of castings, and this waste casting sand must be removed from the production site [11-13]. The physical-chemical deterioration of the used sand, contact with molten metal at a temperature of around 1500°C [14], a loss of binding power of the bentonite in the molding sand and mechanically breaking of the sand grains are all undesirable situations [15]. In addition, the low strength of the molding sand causes surface defects in the part [16].

After being used in the foundry industry, foundry sand is discarded into storage areas. Waste foundry sand (WFS) generated in large quantities is stored in regular storage facilities without re-evaluation. Over 100 million tons of WFS is produced annually in the world-wide foundry sector. Due to the increasing amount of waste, increasing storage costs, and insufficient storage areas an important environmental and economic problem is created. Therefore, ensuring that this sand is recycled and used, turning it into useful products with economic value, and reducing the consumption of natural materials is an important issue. In addition, it is clear that this recycling will provide great savings in terms of production and waste disposal costs [17].

WFS was studied for use in similar applications such as the production of concrete in the construction sector, structural fillings in road construction, and covering material in the ceramics and glass sectors [17]. In addition, foundry sands are potentially precursors, fillers or aggregates for geopolymer mortars [18].

WFS is useful as a construction material due to enhanced compressive and flexural strength in mortar and concrete respectively [19].

Srinivasan et al. studied engineering stones from waste foundry sand by using an epoxy-phenalkamine binder and suggested that it could be the best alternative material over natural and artificial stones due to its high potential in performance [19].

Studies on the recycling of WFS in different sectors are insufficient. Vijayakumar et al. extracted silicon from foundry sand with magnesium, the silicon was converted into silica, and finally SiC was produced by the reaction between silica and carbon particles [20]. Hossain et al. synthesized SiC using automotive waste glass (rich in silica) and waste coffee grounds (rich in carbon) [21].

In our previous work, different from this publication, the production of a phenolic resin-based abrasive by recycling solid waste casting sands was studied, and the Silicon Carbide (SiC) phase formation was investigated by obtaining C from phenolic resin and silica from solid waste casting sand. This study is also important in the prevention of environmental problems caused by the solid waste of molding sand and to produce abrasives economically by recycling waste.

The phenolic resin has great hardness, compressive strength, corrosion resistance, good heat resistance, and is used as a matrix in friction materials [22].

SiC ceramics have important properties, such as a high elastic modulus, fracture toughness, hardness, good thermal and chemical stability, low thermal and electrical conductivities and low thermal expansion coefficients [23].

Silicon carbide (SiC) is a synthetic material developed for engineering applications and was first obtained by Acheson in 1883 [24].

Silicon carbide is one of the hardest high-tech ceramics and has been a competitor and complement to sintered silicon carbide abrasive synthetic diamonds. This product, which was found in studies to obtain extremely hard materials by the reaction of clay and carbon, was named Carborundum. The invention was made by giving a high current to the carbon electrode placed between the clay-coke mixture placed in an iron bowl that served as an electrode. This was then analyzed and formulated as SiC and later patented under the name Carborondum. SiC is mixed with high-purity quartz, quality coke, or anthracite and produced in Acheson furnaces at temperatures above 200°C. Silicon carbide ceramics are required for many difficult application areas due to their high thermal conductivity and superior corrosion resistant properties. Silicon carbide (SiC) or carborundum is a synthetic abrasive produced by the fusion of high-grade silica sand and finely ground carbon (petroleum coke) in an electric furnace at high temperatures (1600-2500 °C) [25, 26].

SiC can be used as an abrasive and a refractory due to its high-temperature properties, low thermal expansion coefficient, and high thermal conductivity [27]. Silicon carbide is also a material used in the processing of materials such as cast iron, non-ferrous metals, glass, rubber, and others. It is also used in processes related to sectors such as electric heating elements, aviation, composite materials, and others. [28].

There are two different crystallographic structures of SiC powders such as noncubic α-SiC and cubic β-SiC. The sintered α-SiC consists spherical grains, whereas the β -SiC consists of

elongated grains that increase the fracture toughness of the ceramics [29].

Silicon carbide has a covalent bond structure and is a material that is difficult to sinter without additives to achieve high density by either a solid-state or liquid-phase sintering mechanism [27].

Different sintering methods result in various properties. For example, high-pressure sintering (HPS) is essential in the production of dense SiC with fine grains and strong intergranular bonding. This can provide the improvement of hardness and fracture toughness of SiC. [29].

With spark plasma sintering (SPS), SiC ceramics can be sintered in shorter periods and at lower temperatures. In this technique, pressure is applied during sintering, while direct current is applied to graphite molds and pressed powders, thereby heating the powders. Since SPS is a fast technique, the microstructure can be easily controlled. As the growth of grains is restricted and the density is increased, the mechanical properties can be improved, and sintering is possible in short periods (5-10 minutes) by applying lower temperatures (1700-1800 °C) [30].

The aim of this study is to obtain an abrasive composite material containing SiC particles embedded in carbon matrix. The innovation lies in the in-situ formation of SiC fillers through the pyrolysis of foundry industry waste sand dispersed in previously cured phenolic resin. Thus, a suitable industrial method has been developed to recover foundry industry waste sand and give it a second life.

2 Materials and methods

The XRF (Brand-Model) analysis results of the waste foundry sand supplied by Kondöksan and the properties of the resol type phenolic resin (ÇZR-8005) supplied by the Çukurova Chemical Industry Joint Stock Company are shown in Table 1 and Table 2.

The XRF analysis of the waste foundry sand (Table 1) shows that the waste mainly contains SiO_2 and Al_2O_3.

Table 1. The XRF analysis result of waste foundry sand

SiO_2	CaO	Al_2O_3	MgO	MnO	Fe_2O_3	SO_3	TiO_2	K_2O	Na_2O	ZrO_2	P_2O_5	Cl	Fire casualties
72.1	1.92	8.83	1.03	0.06	4.69	0.36	0.67	0.57	0.92	0.04	0.31	0.06	8.41

Table 2. The Properties of ÇZR-8005 Phenolic Resin

Molar Ratio of Phenol	% 31
Molar Ratio of Formaldehyde	% 60
Solid Content	% 75-80
Gelation Temperature	49 °C.dk^{-1}
Density	20 °C-1.20 / -1.30 g.ml^{-1}
Viscosity	25 °C-800-1000 Pa.s

Foundry waste sand supplied by the Kondöksan company was separated into different grain sizes using the Retsch AS200 brand vibrating screen system, and studies were carried out using sub-63 micron particle size powders.

Firstly, based on a 2/1 resin/waste ratio, reference (R, R-A coded) abrasives were produced using waste sand and resin with and without active carbon. In the first stage, resin, powder additive, and ethyl alcohol (5% by weight) were homogenized using an İTK-MK350 brand heated magnetic mixer at 50°C for thirty minutes to prepare the mixture. Alcohol was initially mixed into the resin, and then waste was added.

The second stage was the casting and curing process. A syringe with an inner diameter of 8 mm was used as a mold. After the casting, the molds were subjected to vibration in an Elmasonic S60H model ultrasonic bath to remove the air bubbles inside. The curing process was carried out in a Binder VD23 brand device at 65 °C for one hundred and twenty hours.

After the curing process, the compositions were subjected to heat treatment at 170 °C for sixteen hours, maintaining their structural integrity. They were subjected to traditional heat treatment without pressure under nitrogen gas in an MSE Furnace ATM-ELV-1700-12-(CH) brand oven for one hour at 600 °C with a heating rate of 5°C.min^{-1}, and at 1000 °C with a heating rate of 3 °C.min^{-1}, respectively (Figure 1).

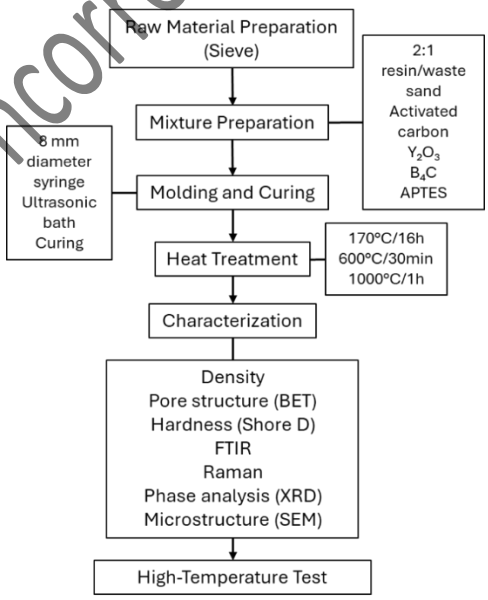


Figure 1. A flow chart of the experimental methods

Literature studies were examined to support the formation of SiC. In a study conducted by Zhu et al., it was stated that the mechanical properties of SiC material increased at 2150°C in the study that was conducted with B_4C and activated carbon additions [31]. In addition, productions were carried out for another study conducted with the addition of Y_2O_3 and Al_2O_3 based on a study conducted by Yun et al. 2021. It was stated that the SiC phase was obtained using Al_2O_3: 58.8, SiO_2: 23, and Y_2O_3: 18.2 by weight [32].

In addition, according to the literature, γ-aminopropyl triethoxy silane (APTES) was added to form cross-linked polymers, improving the crosslinking density of the resins and polymeric modification. APTES is a widely used coupling agent due to its amino group. Amino-terminated silica particles can be used as fillers in rubber and plastic to increase tensile strength and wear resistance as well as improving rheological behavior [33, 34]. APTES is the most widely used silane

molecule to functionalize oxide surfaces [35]. Oxide surfaces have high surface energy hydroxyl groups (-OH) that can rapidly interact with silane molecules and form a covalent bond [36].

Considering the literature studies, in this study, abrasive production was also carried out by adding B_4C+activated carbon and B_4C+activated carbon+APTES, and adding Y_2O_3+Al_2O_3, Y_2O_3+Al_2O_3+APTES. All the compositions produced are shown in Table 3. In addition, all the abrasive compositions mentioned were mixed using ethyl alcohol.

Table 3. Recipes of all produced compositions

Sample Code	R	R-A	Y	Y-G	B-A	B-A-G
Content	Resin/Waste	Resin/Waste + Activated Carbon	Reference + Al_2O_3 + Y_2O_3	Reference + Al_2O_3 + Y_2O_3 + APTES	Reference + B_4C + Activated Carbon	Reference + B_4C + Activated Carbon + APTES

The samples produced with B_4C and Y_2O_3 additives were left to cure for one hundred and twenty hours at 65 °C and then for sixteen hours at 170 °C. After this, the samples were heated to 600°C at 5 °C.min^{-1} and kept at this temperature for thirty minutes, after which the temperature was increased to 1000 °C at 3°C.min^{-1} and kept at this temperature for one hour. The high-temperature processes were carried out in an Optosense brand oven under an argon atmosphere.

The raw materials used in the study include 3-aminopropyltriethoxysilane (APTES) supplied by ROTH, with a molecular weight of 221.37 g.mol^{-1}. Yttrium oxide (Y_2O_3) was purchased from Nanokar, with a purity of 99.9% and an average particle size of ten microns. Boron carbide (B_4C) was also obtained from Nanokar, with a purity of 99.5% and an average particle size of one hundred microns. Alumina was supplied from Global Monarch with a purity of 99% as white fused alumina powder. The Alumina and Norit brand activated carbon grain sizes were below 63 microns.

For the material coded B-A-G, it could not be performed due to foaming and hand disintegration, and for other abrasives produced with Y, Y-G, and B-A and additives:

- Sample density Helium pycnometer Micromeritics–Accupyc2 1340,
- Pore structure and distribution BET Quantachrome–Quadrasorb Evo 4,
- Hardness measurement Loyka LX-D-2 brand Shore D device,
- Surface functions FTIR Fourier Transform Infrared Spectrometer (FT-IR Thermo Scientific–Nicolet iS20),
- Development of carbon-carbon covalent bonds in the structure and 3D distribution of particles in the matrix Confocal RAMAN Renishaw by way of a Reflex Confocal Raman Microscope,
- Phase analysis XRD PANalytical EMPYREAN
- Microstructural examinations SEM Hitachi–SU 1510 were measured (Figure 1).

As a result of the experimental studies, to understand whether the resin could withstand the high temperatures required for SiC powder synthesis, the resin was cured on its own for one hundred and twenty hours at 65 °C and for sixteen hours at 170 °C. After this, heat treatment was applied under a vacuum at a heating rate of 5°C.min^{-1} for thirty minutes at 600 °C, one hour at 1000 °C with 10 °C.min^{-1}, and one hour at 1500 °C after sweeping.

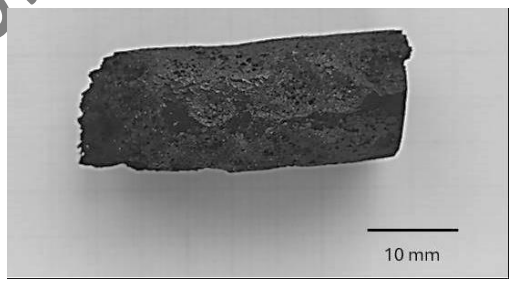
3 Results and discussion

The densities of the produced materials were examined, and the analysis results made with the Helium pycnometer are shown in Table 4. The Y_2O_3 added material is denser compared to the other produced materials. In addition, APTES creates a higher crosslinking density of resin. All the compositions with additives were measured as denser than the reference material.

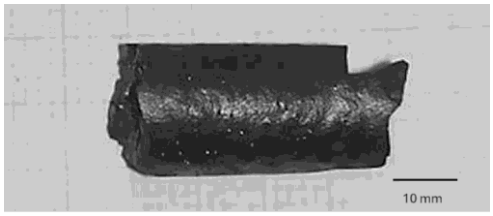
İn order to densify SiC at lower sintering temperatures, sintering additives were used. Sintering additives such as Y_2O_3 could form liquid-phases, the eutectic reactions were below 2000 °C and then enhanced particle rearrangement and densification by way of capillary action during Liquid-phase sintering was conducted [37].

Table 4. The pycnometer densities of the produced samples

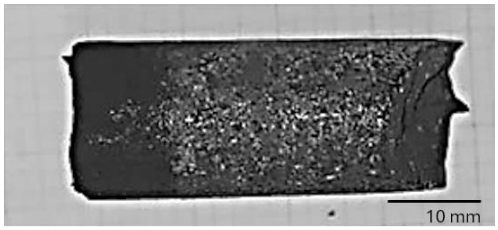
Material	R	Y	Y-G	B-A
Density (g.cm^{-3})	0.7611	1.7631	1.7621	1.3589



(a)



(b)



(c)

Figure 2. The images of a) R, b) Y, and c) B-A materials after 1000 °C heat treatment

During the experimental studies, it was observed that a more viscous mixture was obtained when preparing the abrasive mixture containing B_4C and that the abrasive was formed on a rougher surface at the end of the heat treatments. It was also observed that the materials with Y_2O_3 additives had smoother surfaces than the materials with B_4C additives as a result of the heat treatment (Figure 2).

The surface roughness/porosities on the surface could influence the hardness of the material (Figure 2, Figure 3, Table 5). Hardness was measured using the Shore D hardness measurement method. Free from fillers, the R sample was the hardest with more than 85 shore D hardness. The addition of Y_2O_3, B_4C, APTES and/or AC reduced the hardness which may decrease down to 75 shore D with Y_2O_3 (Y) and below 60 shore D with the combination of B_4C and APTES (B-A) (Figure 3).

The residual stresses generated by the formation of multiple secondary phases could reduce the hardness that can change in grain boundaries because of the sintering additives in SiC ceramics. The hardness of the B_4C-SiC composites degraded with mixed Al_2O_3-Y_2O_3 additives [38] are similar to our results.

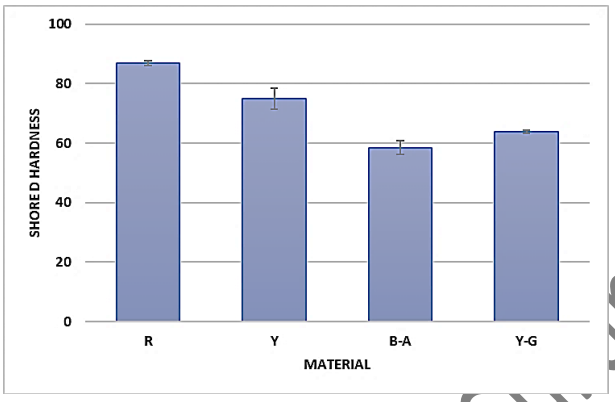


Figure 3. The Shore D hardness measurement values of the samples

Table 5. The BET Analysis Results

Material	Y-G	B-A	Y	R
BET surface area ($m^2.g^{-1}$)	50	41	48	3
Adsorption Average Pore Width (4V/A by BET) (nm)	3.06	2.89	3.09	0

The BET analysis results obtained by applying gas adsorption to the composite materials show that the matrix is affected by the additives (Table 5). The specific surface area of all the composites is higher than the reference material. This increase is higher in those structures containing Y_2O_3 supporting a chemical interaction. It is thought that the interaction with B_4C may be more physical. A high amount of pore former like active carbon will increase the total pore volume and large pores in the SiC material [39]. Additionally, lowering of the reaction temperature by sintering additives may promote a higher surface area [40].

After density, the hardness and BET measurements, FT-IR analysis of the produced materials was performed. A graph drawn in line with the data obtained after the analysis is shown in Figure 4.

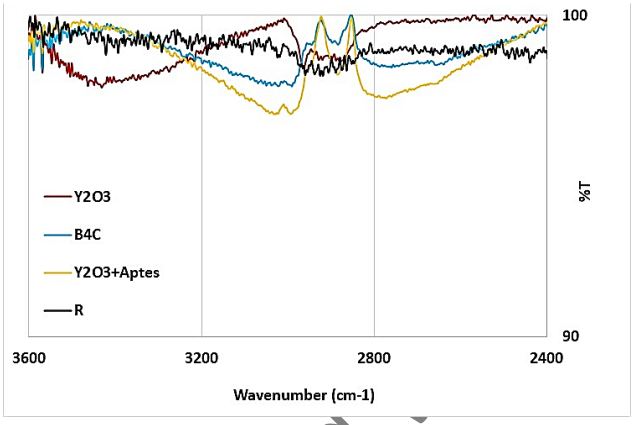


Figure 4.The FT-IR analysis results of the produced materials

The FTIR peaks observed above 2500 cm^{-1} are typical from the single bonds (C-H, O-H, N-H…) present in the chemical structures [41]. The R sample does not present marked peaks in this spectrum domain indicating a successful polymerization and carbonization during the heat treatment. Concerning the Y sample, the addition of both Al_2O_3 and Y_2O_3 promoted the presence of peaks at about 3400, 3100 and 2900 cm^{-1}, which are characteristic of both additives [42, 43]. The peak at 3400 cm^{-1} disappeared when APTES was introduced in the Y-G sample suggesting a chemical structure modification due to a reaction with the oxides. However, the reaction did not affect the APTES structure where characteristic peaks in the 2900-3000 cm^{-1} were present [44]. The presence of these peaks supports the bonding role of APTES which creates chemical bridges between the matrix and the oxide fillers. Finally, the peaks between 2900-3100 cm^{-1} in the FTIR spectrum of the B-A sample suggest the B_4C structure remains during the process [45].

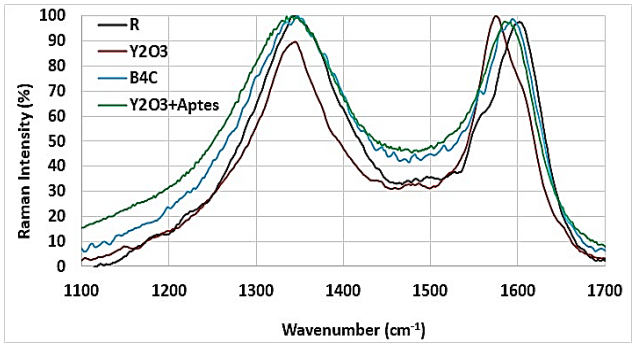


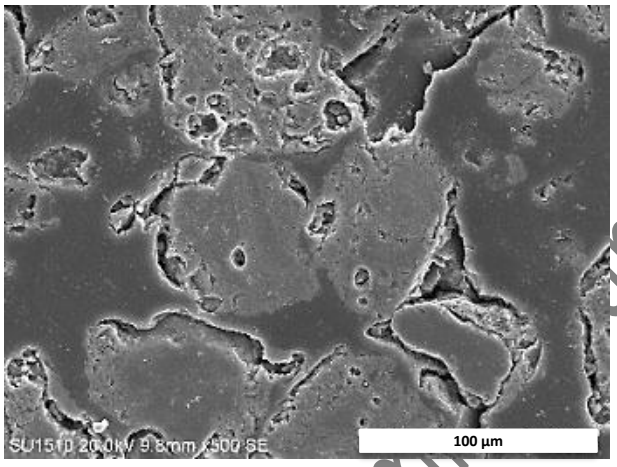
Figure 5. The Raman analysis results of the produced materials

Although they were prepared under the same conditions, it was seen that the characteristics of the C-C bonds in the matrix changed according to the additive materials. In the Raman spectrum, the G (1580 cm^{-1} - C_{sp2}) band represents regular/aromatic structures, while the D (1350 cm^{-1} - C_{sp3}) band shows the irregularities of the carbon structure, amorphous structures and structures that change as a result of oxidation [46]. Since the ID/IG signal intensity ratios are

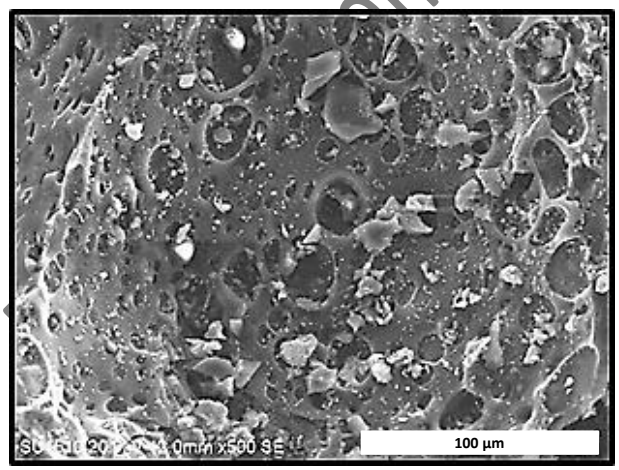
parallel to the C_{sp3}/C_{sp2} ratios in the structure, the ID/IG ratios that can be calculated from the material spectra are compared with each other and used to evaluate the structural irregularity in the matrix. While the ID/IG values are at the level of 1.12 in the Y_2O_3 doped material, this value is approximately 0.98 with the other materials. Therefore, it is thought that the matrix contains more C_{sp3} when doped with Y_2O_3, and this can only be due to an interaction between the matrix and the additive material.

The fact that the ID/IG ratios in the reference, Y_2O_3+APTES, and B_4C materials are almost unaffected shows that the matrix structure is not affected by the additives; that is, there is no reaction between the additive and the matrix. In particular, the fact that the amount of C_{sp3} does not increase in the Y_2O_3 doped material with the addition of APTES is supported by the Raman results (Figure 5), which show that the APTES doping reduces the reactivity of the Y_2O_3 material, consisting of the FTIR results.

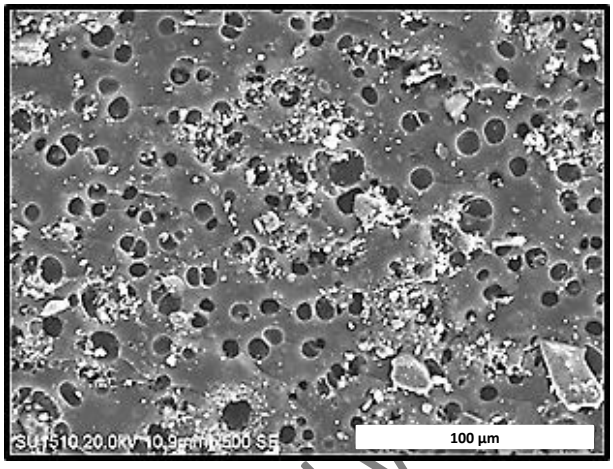
The change in material properties with the increase in specific surface area and average pore width values is also reflected in the SEM images and it was observed that pores were formed in welded structures (Figure 6).



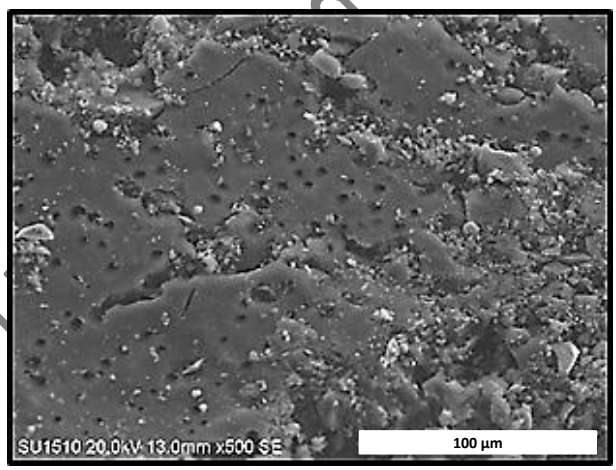
(a)



(b)



(c)



(d)

Figure 6. The SEM images of a) R, b) B-A, c) Y and d) Y-G

The SEM analyses of the materials are shown in Figure 6. When the microstructures were examined, it was observed that a small number of macro pores occurred on the surface of the reference material where cracks formed. It was observed that the pores became more pronounced with the additives. When the image produced with the Y_2O_3 additive was examined, it was seen that the pores were relatively smaller. It was further seen that the pores observed in the microstructure also supported the BET results.

The waste casting sands and other additives (B_4C, Y_2O_3 and APTES) mixed in the phenolic resin matrix were cured as a result of the polycondensation reaction above 100°C after mixing. The released water molecules evaporated at this temperature and moved away from the composite material, forming spherical pores on the surface of the material (Figure 6). However, the sizes and distribution of the pores formed due to the possible changes in the matrix viscosity and mechanical properties due to the effect of the B_4C, Y_2O_3 and APTES additives change. While the pores in the B_4C-added composites are large and their distribution is heterogeneous, the pores in the Y_2O_3-added composites are both smaller and their distribution is more homogeneous. In addition, the number and size of the pores were further reduced with the addition of APTES.

The XRD analysis results of the produced materials are shown in Figure 7. When the XRD analysis results are examined, SiC peaks are observed in the B-A sample incorporating B_4C and active carbon as sintering additives, but there were no SiC peaks in any of the samples. The reason for this is thought to be insufficient heat treatment in order to make the complete conversion of the raw materials into silicon carbide. When the literature is examined, since the abrasive properties of the final abrasives are intended to be provided with SiC additive particles, the SiO_2 particles forming the waste sand should react with carbon at a temperature of at least 1200 °C [47].

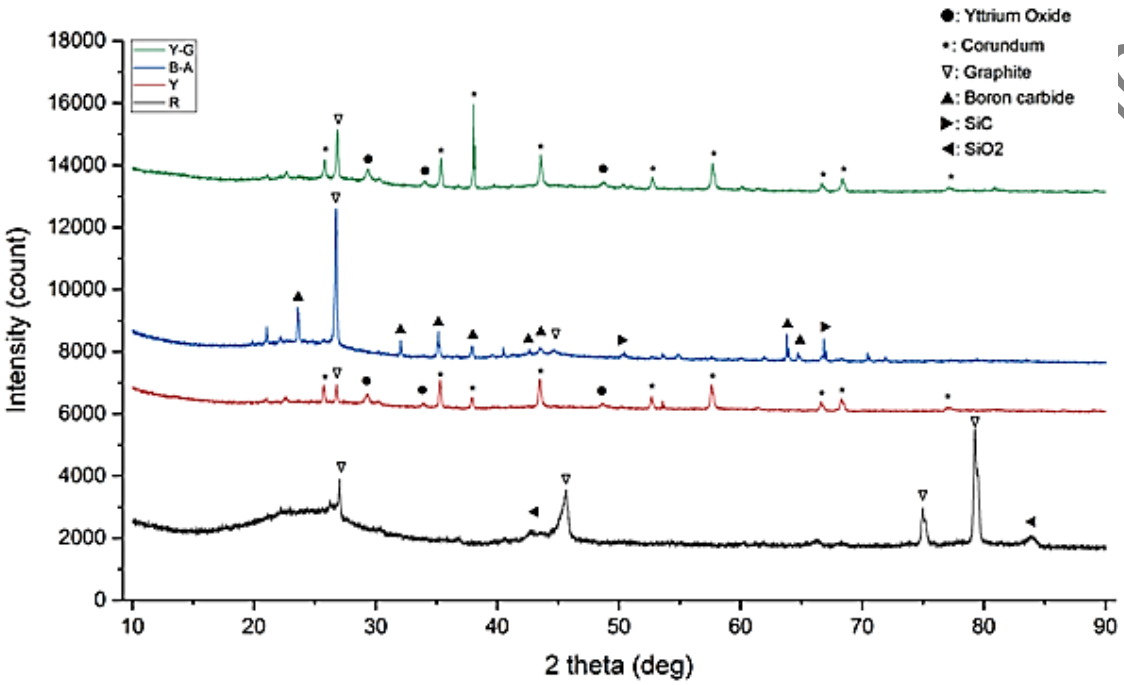


Figure 7. The XRD analysis of a) R, b)Y, c) Y-G and d) B-A.

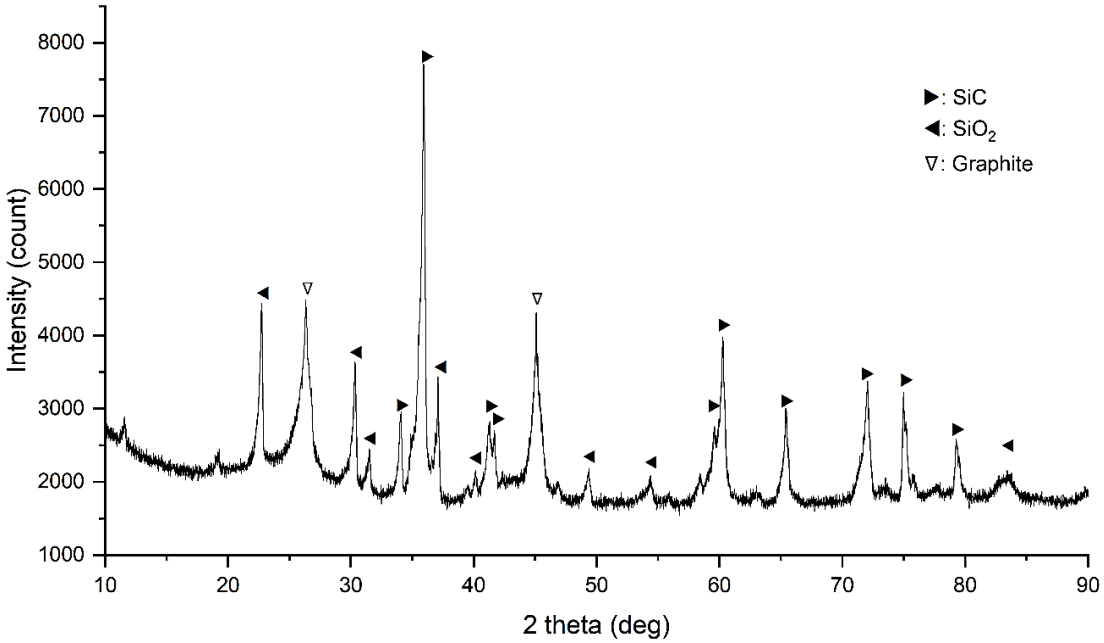


Figure 8. The XRD analysis of the reference material after 1500 °C heat treatment.

As a result of the analysis, the presence of the SiC peak was detected and it was thought that it would be appropriate to carry out the heat treatment at 1500 °C for 1 hour. However, the material that reached this temperature disintegrated in the hand.

In order to understand whether the resin could withstand the high temperatures required for SiC powder synthesis, the resin was cured on its own at one hundred and twenty hours at °C and sixteen hours at 170 °C. After this, heat treatment was applied under a vacuum after sweeping at 600 °C for thirty minutes and 1000 °C for one hour at a heating rate of 5 °C.min^{-1}. As can be seen in Figure 9, the resin breaks down at high temperatures. Therefore, as a result of the studies, it would be more suitable to produce perform SiC powder synthesis and then convert it into abrasive form with resin.

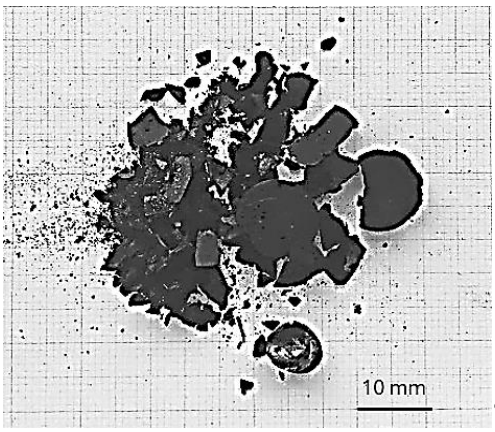


Figure 9. An i*mage of resin heat treated at 1500 °C*

4 Conclusions

For abrasives produced with Y_2O_3, B_4C, and Y_2O_3+APTES additives, it was observed that the material incorporating of the Y_2O_3 additive was denser. Sintering additives such as Y_2O_3 could form liquid-phases and enhance densification of SiC. Sintering additives could decrease the hardness of SiC due to generated residual stresses. The surface roughness/porosities on the surface could also influence the hardness of the material.

The specific surface area (BET) and the pore size of all the composites is higher than the reference material. Former additives such as active carbon may increase the total pore volume and large pores in the SiC material.

According to the FTIR analysis result, considering the electronegativity differences of boron and carbon as well as the electronegativity differences of Y_2O_3 and carbon, the B-A_is weakly polar bonded while the Y-G is a stronger polar. While the Y_2O_3 is well dispersed throughout the structure, the B_4C tends to form agglomerations. The carbon bonding rates of the B_4C and Y_2O_3+APTES additives are extremely close. When the BET analyses were examined, the pore amount was seen to be slightly lower in the B_4C. The APTES additive showed a pore-filling effect in the material. When the XRD analysis results were examined, no SiC formation was observed in the entire structure. This was thought to be due to an insufficient temperature. According to the results of the SEM analysis, while the pores in the B_4C-added composites are large and their distribution is heterogeneous, the pores in the Y_2O_3-added composites are both smaller, and their distribution is more homogeneous. In addition, the number and size of pores are further reduced with the addition of APTES. Considering these developments, it is thought that the composite properties change due to the effects of the additives.

As a result of the experimental studies, it was determined that the resin did not withstand the high temperatures for SiC powder synthesis, and it was predicted that it would be more appropriate to perform the SiC powder synthesis first and then convert it into an abrasive form with resin.

5 Acknowledgement

6 Author(s) Contribution Statement

In this study, Author 1 contributed to the creation of the idea, design, procurement of resources and materials, data collection, analysis, literature review and writing stages. Author 2 completed the stages of design, supply of resources and materials, data collection, analysis, literature review, writng. Author 3 carried out design, data collection, analysis, literature review, writing stages. analysis, Author 4 contributed to the design, data collection, interpretation of analyses, literature review, writing stages.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain ethics committee permission for the article prepared."

"There is no conflict of interest with any person/institution in the article prepared."

8 References

[1] Sylvia JG. Cast Metals Technology. Pennsylvania, U.S, Massachusetts:Addison-Wesley, 1972.

[2] Kepez Ü. "Türkiye'de Döküm Sektörü - Demir Döküm". TÜBİTAK Metal Teknoloji Platformu Oluşturma Çalıştayı, Kocaeli, Türkiye, 23-24 Şubat 2007.

[3] Bolat Ç, Bekar C, Gökşenli A. "Mechanical and physical characteristics of bubble alumina reinforced aluminum syntactic foams made through recyclable pressure infiltration technique". Gazi University Journal of Science, 35(1), 184-196, 2022.

[4] Bolat Ç, Akgün İ. C, Gökşenli A. "Effects of particle size, bimodality and heat treatment on mechanical properties of pumice reinforced aluminum syntactic foams produced by cold chamber die casting". China Foundry, 18(6), 529-540, 2021.

[5] Kumar D, Seetharam R, Ponappa K. "Effects of graphene nano particles on interfacial microstructure and mechanical properties of Al7150/B_4C hybrid nanocomposite fabricated by novel double ultrasonic two stage stir casting technique". Journal of Alloys and Compounds, 1008, 176686, 2024.

[6] Lai K C, Tsai C, Yen S Y, Tseng K K, Yeh J W, Chen P Y. "Fabrication of novel 316L stainless steel scaffolds by combining freeze-casting and 3D-printed gyroid templating techniques". Materials Science and Engineering: A, 915, 147200, 2024.

[7] Aran A. Döküm Teknolojisi İmal Usulleri Ders Notları. İTÜ Makine Fakültesi, İstanbul, Türkiye, 2007.
[8] Aran A. Metal Döküm Teknolojisi. İTÜ Makine Fakültesi Ofset Atölyesi, İstanbul, Türkiye, 1989.
[9] Zanetti MC, Fiore S. "Foundry processes: The recovery of green moulding sands for core operations". Resources, Conservation and Recycling, 38(3), 243-254, 2003.
[10] Siddique R, Schutter G, Noumowe A. "Effect of used-foundry sand on the mechanical properties of concrete". Construction and Building Materials, 23(2), 976-980, 2009.
[11] Siddique R, Kaur G, Rajor G. "Waste foundry sand and its leachate characteristics". Resources, Conservation and Recycling, 54(12), 1027-1036, 2010.
[12] Clegg AJ. Precision Casting Processes. New York, U.S, Pergamon Press, 1991.
[13] Guney Y, Sari YD, Yalcin M, Tuncan A, Donmez S. "Re-usage of waste foundry sand in high-strength concrete". Waste Management, 30(8-9), 1705-1713, 2010.
[14] Dungan RS, Huwe J, Chaney RL. "Concentrations of PCDD/PCDFs and PCBs in spent foundry sands". Chemosphere, 75(9), 1232-1235, 2009.
[15] Dayton EA, Whitacre SD, Dungan RS, Basta NT. "Characterization of physical and chemical properties of spent foundry sands pertinent to beneficial use in manufactured soils". Plant Soil, 329(1), 27-33. 2010.
[16] Şençoban Kaya S, Alaykıran K. "Hata türü ve etkileri analizi ve döküm sektöründe bir uygulama". Necmettin Erbakan Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, 1(2), 76-89, 2019.
[17] Alias C, Cioli F, Abbà A, Feretti D, Sorlini S. "Ecotoxicological assessment of waste foundry sands and the application of different classification systems". Integrated Environmental Assessment and Management, 20(6), 2294–2311, 2024.
[18] Sgarlata C, Ariza-Tarazona MC, Paradisi E, Siligardi C, Lancellotti I. "Use of Foundry Sands in the Production of Ceramic and Geopolymers for Sustainable Construction Materials". Applied Sciences, 13, 516, 2023.
[19] Srinivasan D, Ramachandran S, Kannadasan K, Muthukaruppan A, Ismail AAM. *"Production of engineered stone from waste foundry sand using epoxy-phenalkamine binder". Construction and Building Materials, 419, 135464, 2024.
[20] Vijayakumar K, Viknesh K, Subash B, Vishnubalan J, Prakash K. "Utilisation of waste foundry sand by converting it to an integrant for grinding application". International Journal of Engineering Research & Technology (IJERT) ETDM-2017, 5(7), 1-4, 2017.
[21] Hossain R, Sahajwalla V. "Molecular recycling: A key approach to tailor the waste recycling for high-value nano silicon carbide". Journal of Cleaner Production, 316, 128344, 2021.
[22] Liu J, Guo J, Deng J, Fan S, Cai X, Kou S, Yang S. "Preparation and Properties of Boron Modified Phenolic Resin for Automotive Friction Materials". Materials (Basel). 18(7), 1624, 2025 .
[23] Zawrah MF, Shaw L. "Liquid-phase sintering of SiC in presence of CaO". Ceramics International, 30(5), 721-725. 2003.
[24] Acheson, E.G., Production of artificial crystalline carbonaceous materials. Patent # 492, 767, 1893.
[25] Ataman Chemicals. "Silicon Carbide". https://www.atamanchemicals.com/silicon-carbide_u26029/?lang=EN (11.11.2024).
[26] Expert. "Metalurjik Silisyum Karbür". https://expert.com.tr/metalurjik-silisyum-karbur/ (11 .11. 2024).
[27] Thulasiraman VA, Ganesapillai M. "A Systematic Review on the Synthesis of Silicon Carbide: An Alternative Approach to Valorisation of Residual Municipal Solid Waste". Processes, 11, 283, 2023.
[28] Kronos Metal. "Siyah Silisyum Karbür". https://kronosmetal.com.tr/tr/urunler/kumlama-ekipmanlari/siyah-silisyum-karbur (11.11.2024).
[29] Sun R, Zhang X, Hao X, Hu W, Wei X, Song X, Zhang Z, Ying P, Zhao S, Wang Y, Gao Y, Yu D, Xu B, Gao G, TianY. "Simultaneously enhanced toughness and hardness of nanocrystalline SiC sintered under high pressure". Journal of the European Ceramic Society, 45, 116829, 2025.
[30] Gençkan HD. Reaktif spark plazma sinterleme yöntemi ile B_4C/SiC kompoziti eldesi. Yüksek Lisans Tezi, İstanbul Teknik Üniversitesi, İstanbul, Türkiye, 2009.
[31] Zhu Y, Luo D, Li Z, Wang Y, Cheng H, Wang F, Chen T. "Effect of sintering temperature on the mechanical properties and microstructures of pressureless-sintered B_4C/SiC ceramic composite with carbon additive". Journal of Alloys and Compound, 820(4), 153153, 2020.
[32] Yun SI, Youm MR, Nahm S, Park SW. "Fabrication and properties of macro-porous SiC using Al_2O_3–Y_2O_3–SiO_2 as bonding additives". Ceramics International, 47(9), 11979-11988, 2021.
[33] Gu N, Zhang H, Ge H, Wang F, Liu B. "In-situ polymerization of graphene/SiO_2 hybrids modified phenolic resin for improved thermal stability at an ultralow filler loading." Polymer Bulletin, 78, 5963–5976, 2021.
[34] Plueddemann EP. Silane Coupling Agents. 2nd ed., New York, USA, Plenum, 1991.
[35] Miranda A, Martínez, De Beule PAA. "Facile synthesis of an aminopropylsilane layer on Si/SiO_2 substrates using ethanol as APTES solvent". MethodsX, 7, 100931, 2020.
[36] Zhang W, Lai EPC. "Chemical functionalities of 3-aminopropyltriethoxy-silane for surface modification of metal oxide nanoparticles". Silicon, 14(12), 6535–6545, 2022.
[37] Shin S, Kim M, Kim M, Kim U, Kim S, Kwak Y, Cho J. "Ultrafast high-temperature sintering of reaction-bonded SiC with Y2O3-Al2O3 sintering additives". Materials Letters, 382, 137956, 2025.
[38] Jamale S, Kumar BVM. "B_4C-SiC composites with tuneable mechanical properties: Role of Al2O3 - Y2O3 sintering additives". Journal of Alloys and Compounds, 976, 172954, 2024.
[39] Nguyen P, Pham C. "Innovative porous SiC-based materials: From nanoscopic understandings to tunable carriers serving catalytic needs". Applied Catalysis A: General, 391, 443–454, 2011.
[40] Parmentiera J, Patarina J, Dentzerb J, Vix-Guterl C. "Formation of SiC via carbothermal reduction of a carbon-containing mesoporous MCM-48 silica phase: a new route to produce high surface area SiC". Ceramics International, 28, 1–7, 2002.

[41] Hynes A, Scott DA, Man A, Singer DL, Sowa MG, Liu KZ. "Molecular mapping of periodontal tissues using infrared microspectroscopy". BMC Medical Imaging, 5(2), 1-10, 2005.
[42] Atrak K, Ramazani A, Fardood ST. "Green synthesis of amorphous and gamma aluminum oxide nanoparticles by tragacanth gel and comparison of their photocatalytic activity for the degradation of organic dyes". Journal of Materials Science: Materials in Electronics, 29, 8347–8353, 2018.
[43] Zhang L, Li Z, Zhen F, Wang L, Zhang Q, Sun R, Selim FA., Wong C, Chen H. "High sinterability nano-Y2O3 powders prepared via decomposition of hydroxyl-carbonate precursors for transparent ceramics". Journal of Materials Science, 52, 8556–8567, 2017.
[44] Zabihi O, Khayyam H, Foxa BL, Naebe M. "Enhanced thermal stability and lifetime of epoxy nanocomposites using covalently functionalized clay: experimental and modelling". New Journal of Chemistry, 3, 2015.
[45] Li X, Jiang D, Zhang J, Lin Q, Chen Z, Huang Z. "The dispersion of boron carbide powder in aqueous media". Journal of the European Ceramic Society, 33 (10), 1655-1663, 2013.
[46] Shahriary L, Athawale AA. "Graphene oxide synthesized by using modified Hummers approach". International Journal of Renewable Energy and Environmental Engineering, 2(1), 58-63, 2014.
[47] Wang F, Xiang D, Wang Y, Li J. "Rapid synthesis of SiC powders by spark plasma-assisted carbothermal reduction reaction." Ceramics International, 43(6), 4970–4975, 2017.