



# On the Investigation of Microstructured Charcoal as an ANFO Blasting Enhancer

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**Abstract:** In this study, we examined the influence of microstructured charcoal (MC) when added to ammonium nitrate fuel oil (ANFO) samples. We performed a study that investigated ANFOs structure, crystallinity, and morphology by utilizing infrared spectroscopy (IR), X-ray diffraction (XRD), and scanning electron microscopy (SEM), respectively. MC characteristics were probed by Raman spectroscopy and SEM analysis. SEM analysis indicated how fuel oil (FO) covered ammonium nitrate prill. Moreover, the surface of the MC was covered by specific microfibers and microtubes. The disordered graphitic structure of the MC was also confirmed by Raman spectroscopy. Simulation of blasting properties revealed that the addition of MC should decrease blasting parameters like heat explosion, detonation pressure, and detonation temperature. However, the obtained differences are negligible in comparison with the regular ANFO. All analyses indicated that MC was a good candidate as an additive to ANFO.

Keywords: ANFO; charcoal; morphology; SEM

## 1. Introduction

Ammonium nitrate fuel oil (ANFO) is one of the most commonly used mining explosives in the world [1]. This might be explained by its low cost and production simplicity, as well as by its good blasting parameters. However, ANFO is also considered as a non-ideal explosive due to its non-ideal detonation behavior. This means that it cannot reach its theoretically predicted values, like the velocity of detonation (VOD) [2].

From a chemical point of view, ANFO is a mixture of ammonium nitrate (recommended porous prill type) with fuel oil (FO) in a weight ratio of 94.5:5.5 that allows for the obtainment of a zero oxygen balance. The zero oxygen balance determines the highest energy value and lowest volume of toxic fumes. However, some additives like various types of metals (e.g., aluminum) can be applied to improve blasting parameters. The application of additives influences the reaction zone that results in a change in the Chapman–Jouguet plain. However, we applied new component results when changing the oxygen balance. The same thing can be assigned when applying various types of fuel oil. Besides an influence on oxygen balance, fuel components have an impact on explosive sensitivity [3]. Improved



sensitivity results in an increased ability of detonation. However, applying some fuels or various additives can decrease sensitivity, which should result in deflagration or misfire.

Chemical explosives (including ANFO) with suitable initiation are subjected to rapid decomposition, matter expansion, and heat and gas production.

Oxley et al. [4,5] indicated that the mechanism of AN decomposition is characterized by both a radical and an ionic reaction. The former reaction is at a high rate and takes place at high temperatures. The opposite effect can be observed for the latter reaction, for which the rate and temperature are low. The melting point of AN is 169 °C and thus AN decomposition is possible. According to Brower et al. [6], at the beginning of a radical reaction, AN undergoes dissociation to HNO<sub>3</sub> and NH<sub>3</sub> (Equation (1)), and subsequently the homolysis of the O-N bond in HNO<sub>3</sub> takes place (Equation (2)). Due to the very high values of HNO<sub>3</sub> homolysis activation energy (ca. 190 kJmol<sup>-1</sup>), this stage is considered as a rate-controlling step. Wada et al. [7] determined the temperature of HNO<sub>3</sub> homolysis as 1300 °C in the flame.

$$NH_4NO_3 \leftrightarrow NH_3 + HNO_3$$
 (1)

$$HNO_3 \rightarrow^* OH + NO_2 \tag{2}$$

In next step, the high-rate radical chain reaction occurs according to Equations (3) and (4).

$$NH_3 + *OH \rightarrow NH_2 + H_2O \tag{3}$$

$$NH_2 + NO_2 \rightarrow [NH_2NO_2] \rightarrow N_2O + H_2O$$
(4)

In the case of  $NH_4NO_3$  ionic reaction, the process begins by the dissociation of AN into  $NH_3$  and  $HNO_3$  (Equation (1)). In the next step,  $NH_3$  oxidation occurs by the products from  $HNO_3$  decomposition (Equations (5)–(7)).

$$2HNO_3 \rightarrow NO_2 + NO_3^{-} \tag{5}$$

$$NO_2 + NO_3^- \rightarrow NO_2^+ + NO_3^- \tag{6}$$

$$NO_2^+ + NH_3 \leftrightarrow [NH_3NO_2]^+ \rightarrow N_2O + H_2O$$
(7)

Bare powders are not able to hold a shape and TNT is often added to enable the formation of melt-castable explosives. According to the existing literature, most of the explosive powders are subjected to plasticization in order to obtain a moldable material. The addition of FO, icing sugar, or aluminum leads to explosive formation at a higher heat and mass release, as well as materials characterized by faster expansion [8].

The applicability of various flammable components has been previously investigated [9,10]. Sinditskii et al. concluded that the content of the flammable component, like charcoal, 2,4,6-trinitrotoluene, fuel oil (diesel), or iron persulfide (II), is indispensable during the detonation process [9]. Gunawan and Zhang noticed that the presence of pyrite in ANFOs chemical composition additionally catalyzes the decomposition reaction of an explosive [10]. The influence of the flammable component on the blasting properties of ANFO has also been studied [11–24]. In the conducted research, the combustible components were coal dust, sugar in the powdered and crystalline forms, aluminum dust, 2,4,6-trinitrotoluene, and fuel oil.

Another example of a component added to AN used to obtain explosives is inorganic carbon. Reiset and Millon [16] indicated that the explosion of AN can occur in the presence of red-hot charcoal or as a result of heating an AN-charcoal mixture to 170 °C. In turn, Izato et al. [17] investigated the influence of carbon on AN decomposition. It was found that neither graphite nor carbon black influenced the studied reaction. It was also shown that adding nanoparticle carbon black powders

or activated carbon (AC) caused the onset temperature of AN decomposition to lower. The process occurs mainly according to the ionic mechanism, as follows. In the liquid phase:

$$NO_2^+ + C \rightarrow CO_2 + 1/2 N_2$$
 (8)

$$NO_{3}^{-} + 1\frac{1}{2}C \rightarrow 1\frac{1}{2}CO_{2} + 1/2N_{2}$$
(9)

In the gaseous phase:

$$2N_2O + C \rightarrow CO_2 + 2N_2 \tag{10}$$

It must be emphasized that the reactions between AN and fuel may occur at temperatures lower than the melting point of AN (169.6 °C). Hussain and Rees [18] indicated the presence of a distinct and exothermic peak at 185 °C for the mixture of AN and charcoal. For comparison, in the case of pure AN, no exothermic peaks were found at the same temperature other than at 140 °C. Lurie and Chang [19] indicated that the introduction of carbon black into AN resulted in the lowering of AN decomposition temperature to 70 °C. The process can be described by (Equation (11)), in which HNO<sub>3</sub> decomposition is crucial:

$$HNO_3 + C_6 \rightarrow C_5 - C = O + HNO_2 \tag{11}$$

Subsequently, C<sub>5</sub>-C=O undergoes oxidation into intermediates in the form of ions and radicals. Furthermore, the formation of low stability ammonium nitrite ( $NH_4NO_2$ ) allows for the production of CO and N<sub>2</sub> [15,20,21]:

$$2NH_4NO_3 + C \rightarrow CO_2 + 2NH_4NO_2 \tag{12}$$

$$NH_4NO_2 \rightarrow N_2 + 2H_2O \tag{13}$$

Miyake et al. [22] performed DSC experiments for AN and AC blends. It was evidenced that a small amount of AC (4%wt.) in the AN-AC mixture did not notably change heat production, but rather caused a shift in the exothermic peak towards a lower temperature (310 °C $\rightarrow$ 200 °C). Further increase of AC content from 7% to 10% wt. led to a significant growth of heat flow (7 W/g $\rightarrow$ 105 W/g), with a simultaneous decrease of the exothermic peak temperature (200 °C $\rightarrow$ 180 °C). Further increase of the amount of AC did not significantly alter DSC results. For high AC content, the temperatures of exothermic peaks were only slightly higher than the melting point (169.6 °C). Miyake et al. [22] also indicated that 7% wt. of AC in the AN-AC system is stoichiometric. Furthermore, they performed measurements in a pressure vessel (200 mL) with 1 g of samples (with various AC contents) at raising temperatures up to 400 °C and a temperature ramp of 35 °C/min. During the increase of AC content from 4% wt. to 7% wt., the highest pressure rise was detected (0.1 MPa $\rightarrow$ 1.6 MPa). Moreover, Izato et al. [15,23] indicated that the type of the applied carbon could also impact the results. In the case of AC, the obtained exothermic effect was the highest, whereas for charcoal and graphite intermediate the effect was the lowest. The obtained results can be explained by the differences in the porous structure of the used carbon.

Adding microstructured charcoal (MC) to the non-ideal explosive's chemical composition should act like an additional fuel component. Moreover, the change in non-ideal explosive density and the influence of MC structure may result in a change of detonation velocity, as well as post-blast fume volume. However, a proper study should confirm the possible application of MC and its impact on non-ideal explosive morphology.

Despite accessing numerous reports concerning ANFO and non-ideal explosives, directly applying MC has not been studied. In this work, we presented the application of a new possible additive. Additionally, the present research shows rare data on the structure of charcoal that is a by-product of dry wood distillation process and is a relatively available material, but was dismissed in the scientific literature due to the overall economic profits determined by other products, such as acidic acid, smoke aromas, etc. The present data shows that this type of carbonized material has a rather complicated though interesting microstructure and a potential as an ANFO additive.

#### 2. Materials and Methods

Ammonium nitrate porous prill (AN-PP) was produced by Yara's International ASA in 2020. It was characterized by a bulk density of  $0.82 \text{ g} \cdot \text{cm}^{-3}$  at 20 °C. Prill diameter did not exceed 1 mm. The moisture content was below 0.3%.

Microstructured charcoal (MC) was supplied by the HI Destilacija Teslić in Bosnia and Herzegovina. MC particles had an irregular shape of a diameter in the range of 1–2 mm. MC characteristics are provided in Section 3.1.

Fuel oil (FO) was produced in 2020 by Silesia Oil Sp. z.o.o. At 40 °C, FO was characterized by the density and kinetic viscosity of 0.8 g/cm<sup>3</sup> and 13.6 mm<sup>2</sup>·s<sup>-1</sup>, respectively. We have reported low-temperature properties of FO in one of our previous works [10]. Fuel oil played the role of the flammable component in ANFO.

All ANFO samples were prepared by blending AN-PP with FO for 20 min at 250 rpm, using a mixer. MC was added to the ANFO at the last 5 min of the blending process. All sample compositions are presented in Table 1.

Sample Name	AN-PP, %wt.	FO, %wt.	MC, %wt.
Sample 1	94.5	5.5	-
Sample 2	94.5	4.5	1.0
Sample 3	94.5	2.5	3.0

Table 1. Non-ideal explosive compositions, %wt.

Scanning electron microscopy (SEM) analysis was made using Nova NanoSEM 200 (5–18 keV). Presented micrographs were taken in a range of magnifications of 100–1000×. Before analysis, all non-ideal explosives were dried and coated with a thin carbon layer. Scans were made under low vacuum, ca. 60 Pa, with a low vacuum detector (LVC), operating in secondary electrons mode. The electron beam voltage was 10 kV.

The Fourier-transform infrared spectroscopy (FT-IR) measurements were performed in an iS-10 spectrometer (Thermo Scientific, Waltham, MA, USA) by the attenuated total reflectance (ATR) technique. The spectrometer was equipped with an MCT detector. FT-IR measurements were conducted in the wavenumber range of  $650-4000 \text{ cm}^{-1}$  with 32 scans per each spectrum.

The crystallinity of the obtained materials was determined using the X-ray powder diffraction (XRD) method with a PANalytical X'Pert PRO MPD diffractometer using CuK $\alpha$  radiation at 40 kV and 30 mA. The XRD experiments were carried out in the 2 $\theta$  range of  $-50^{\circ}$  with 0.033° step. The studied ANFO samples were in powder form.

Raman measurements were conducted with a micro-Raman Horiba LabRAM HR spectrometer, equipped with a Peltier-cooled CCD detector. For excitation, the 632.8 nm line of a He-Ne laser line was focused with a 100× objective and a power of 0.4 mW on sample.

Thermodynamic models were established via the ZMWCyw software. The software was developed by the Military University of Technology in Warsaw. Based on the physicochemical properties of individual components, which are included in the ZMWCyw database or input by the user, ZMWCyw software allows for the calculation of non-ideal explosive properties, such as standard energy, explosion pressure, explosion temperature, heat explosion, post-blast volume, and density. The oxygen balance of the non-ideal composition was evaluated based on the standard [25].

#### 3. Results and Discussion

#### 3.1. Microstructured Charcoal Characteristics

SEM images illustrated in Figure 1a,b indicate relative parallel channels and grooves along the MC surface. Closer magnification of 1000× and 5000× (Figure 1c,d) reveal that the fibrous structures are present at certain places along the surface. This finding indicates that some kind of carbon microfibers

or microtubes are formed from the cellulose fibrils in this classical process of the dry wood distillation, which has never been reported before. Magnifications of 10,000× and 20,000× show even a more complex structure. Macro- and mesopores were visible (Figure 1e,f). Thickness of the walls, which were visible from the vertical bird view, showed sizes of approximately 50–500 nm. This well-developed structure should contribute to the process of mixing with explosives since more extended surface and maybe even some active sites should be available.



**Figure 1.** Scanning electron microscopy (SEM) images of microstructured charcoal (MC) at a magnification of (**a**)  $100\times$ , (**b**)  $1000\times$ , (**c**)  $1000\times$ , (**d**)  $5000\times$  (**e**)  $10,000\times$ , and (**f**)  $20,000\times$ .

Wang et al. [26] also obtained carbon microfibers via wet blending of precursors consisting of cellulose and lignin nanofibrils. The obtained mixture was carbonized at 900 °C. The presence of lignin had a notable impact on the morphology of bicomponent microfibers. Carbon microfibers of high density were characterized by the occurrence of circular cross sections without interfiber fusion.

The production of carbon microtubes in the presence of Au nanoparticles was reported by Hurtado et al. [27]. In the synthesized systems, the sucrose was applied as a carbon source. It was found that the utilization of sucrose in low concentrations led to the production of carbon microtubes with diameters of  $0.8-1.5 \mu$ m. Furthermore, uniform distribution of Au nanoparticles was found.

The Raman spectrum of the sample is illustrated in Figure 2. The so-called G-band, a typical of a stretching vibration of the sp<sup>2</sup>-hybridized carbon atoms, was observed at 1592 cm<sup>-1</sup> and was quite sharp and pronounced. On the other hand, the occurrence of D-band at 1342 cm<sup>-1</sup> corresponded to the disordered or sp<sup>3</sup>-like carbon atoms [27–31], and was rather intense, broad, and asymmetric.



Figure 2. The Raman spectrum of the MC sample.

Our Raman results are compatible with those reported by Hurtado et al. [27], Zhu et al. [32], Gentoiu et al. [33], and Nasri-Nasrabadi et al. [34], regarding systems containing micro/nano structured carbon. More specifically, Zhu et al. [32] synthesized carbon nanostructures on Ni-plated commercial hard metal YG6 (WC-6 wt% Co) using a simple ethanol diffusion flame technique. It was found that the deposition duration caused both a higher quality and degree of graphitization of flame deposited carbon nanostructures. Gentoiu et al. [33] synthesized carbon nanomaterials via injection of acetylene and hydrogen into an argon plasma. At 200 °C, the production of vertical aligned carbon nanotubes was found due to plasma activation. At 300–400 °C, only the presence of amorphous carbon nanoparticles was detected. Rising temperature resulted in the transformation of amorphous carbon into graphite with simultaneous production of carbon nanowalls, which took place at temperatures higher than 500 °C. The obtained carbon nanomaterials were characterized by a desirable quality of thickness, H:C ratio, and degree of graphitization. Finally, Nasri-Nasrabadi et al. [34] prepared a nanogrooved surface carbon microtube over polymeric matrices using the sonochemical technique. It was indicated that nanogrooving led to an increase of the cohesion between carbon microtubes and polymer matrix via the formation of bonding sites followed by the generation of networks with polymer chains. This simplifies the extrusion processing of carbon tubes. The modified microtubes were characterized by a high surface area and extruded homogeneity. Carbon tubes obtained by this method can be helpful when producing composite solutions of high rheological stability that allows for the omission of time requirements during the extrusion procedure.

### 3.2. ANFO and Non-Ideal Explosive Characteristics

In all studied samples (Figure 3), IR bands at  $3230-2852 \text{ cm}^{-1}$  were a result of both an asymmetric stretching and an asymmetric deformation vibration of NH<sub>4</sub><sup>+</sup>. The weak band at 1753 cm<sup>-1</sup> was assigned to the stretching vibration and in-plane deformation of nitrate anions or the combination of an asymmetric deformation of ammonium cations. Apparent signals at 1410 and 1290 cm<sup>-1</sup> demonstrated the degenerate deformation of NH<sub>4</sub><sup>+</sup> along with the stretching vibration of NO<sup>3-</sup>. The maxima at 1041 and 825 cm<sup>-1</sup> reflected a symmetric in-plane stretching and an out-of-plane deformation of NO<sup>3-</sup>, respectively [35–37].



**Figure 3.** FT-IR spectra of: (**a**) ANFO, (**b**) AN-PP, (**c**) non-ideal explosive with ca. 1.0% of MC, and (**d**) non-ideal explosive with ca. 3.0% of MC.

Introducing FO generated the band at 1636 cm<sup>-1</sup>, which corresponded with the literature regarding nitration reaction in fuel oils. In the present case, it arose from the reaction with ammonium nitrate already in the mixture preparation phase.

Introducing both concentration combinations (1% or 3%) of microstructured charcoal into ammonium nitrate led to a slight increase of the bands at 2951 and 2852 cm<sup>-1</sup> assigned to stretching vibrations of -CH<sub>2</sub>- and -CH<sub>3</sub> [38]. These bands are the characteristics of the aliphatic branches at the edges of the pyrolysis-based carbon materials. They are useful to confirm the presence of carbon and its relatively preserved characteristics within the explosive mixture. The rest of the bands attributed to FO probably overlapped with the bands originating from AN skeletal vibrations. From the FT-IR analysis, we can conclude that adding MC did not affect the ANFO structure.

The analysis of XRD patterns confirms the presence of a crystalline AN phase in the studied samples (Figure 4, profiles a–d). According to the literature, the crystalline AN is represented by the IV phase and is characterized by the P<sub>mmm</sub> space group, as well as the orthorombic crystal system [39,40]. The diffraction peaks at  $2\theta = 18^{\circ}$ ,  $22^{\circ}$ ,  $24^{\circ}$ ,  $29^{\circ}$ ,  $31^{\circ}$ ,  $33^{\circ}$ ,  $36^{\circ}$ , and  $40^{\circ}$  correspond to the





**Figure 4.** XRD profiles of: (a) ANFO, (b) MC, (c) non-ideal explosive with ca. 1.0% of MC, and (d) non-ideal explosive with ca. 3.0% of MC.

Adding MC into ANFO (Figure 4c,d) caused intensity changes in XRD reflections without any apparent shift. Different observations were reported by Xu et al. [41], who investigated the influence of adding organic potassium salts on the phase stability of AN. They indicated that the application of additives had a strong impact on AN since a phase transition takes place via polar groups forming new hydrogen bonds, which influenced the interaction between ammonium and nitrate ions. From the results reported by Xu et al. [41], we concluded that introducing additives into the AN structure led to more pronounced structural changes, and hence the appearance of the corresponding XRD patterns, with respect to the bare AN. However, in the case of our ANFO-based samples, it is apparent that their structure was preserved and all prepared materials were characterized by high crystallinity.

The crystal surface of ammonium nitrate porous prill was characterized by a large number of surface deformations. Some of the cracks on the crystal surfaces merged and created small cavities. The crystal surface of the prill was wrinkled and highly porous [1,2,43–45]. The addition of fuel oil (Figure 5a,b) indicated that all surface deformations of ammonium nitrate prill were filled with FO. FO was then absorbed by the pores present both on the surface and in the prill's cross-section. Pores in the case of ANFO were considered to act as a hot spot due to shock wave propagation. Moreover, the compression that appeared during shock wave propagation provided the local increase of temperature and pressure that resulted in easier detonation propagation. Miyake et al. [2] indicated that the formation of the hot spot is influenced by the size and volume of the pore, which exists after mixing with oil. They concluded that the pore is relatively small, the oil is restrained from permeating into the particle because of the surface tension, and, subsequently, the rest of the voids could act as hot spots [2]. FO did not dribble from ammonium nitrate (Figure 5a,b). Adding MC into ANFO did not change the morphology of the sample (Figure 5c,d). Fuel oil, similar to pure ANFO, filled all prill surface deformations. However, Figure 5c indicates the presence of both FO and microstructured

charcoal fines on the prill's crystal surface. A small amount of MC powder could be a result of grinding during the mixing process. As in the case of ammonium nitrate, the MC surface was filled with FO (Figure 5e). FO should be absorbed by the porous MC (Figure 5f). FO did not dribble from the surface of non-explosive samples when MC was added.





**Figure 5.** SEM images of (**a**) ANFO at 200× magnification, (**b**) ANFO at 500× magnification, (**c**) non-ideal explosive with 1% of MC at 350× magnification, (**d**) non-ideal explosive with 3% of MC at 1000× magnification, (**e**) MC in non-ideal explosive at 1000× magnification, and (**f**) MC in non-ideal explosive at 5000× magnification.

Table 2 sumarizes the calculated blasting properties and indicates MCs potential influence on the non-ideal explosive properties. Adding MC to the non-ideal explosive composition should cause a decrease in explosive density. This could explain the differences in densities between MC (density is lower in comparison to the fuel component) and FO. The intensity decrease should result to a potential decrease of the velocity of detonation (VOD). Moreover, a decrease of energy with increasing MC content should probably result in a decrease of enthalpy, which may influence critical diameter and explosive sensitivity. This means that when MC content increases, the non-ideal explosive should be less sensitive expected theoretically expected, and thus it should require higher heat of explosion from the primer. Furthermore, the performed simulations show that the enthalpy decreases with MC addition. However, despite this fact, MC should combust behind the reaction front. This can be explained by chemical reaction model in non-ideal types of explosive materials, where each individual component of an explosive material can be characterized by the limited or even lack of blasting ability [46]. In normal conditions, when the inert component of a high standard enthalpy of formation is added to the explosive composition, an increase in detonation temperature and pressure should take place. In this scenario, the rise of temperature appears until the additive component is completely burnt near the Chapman–Jouguet plain. A further decrease of temperature and pressure should be followed by a decrease in the VOD, which can be explained by an increased active surface of the inert component. An increased surface should cause an increase in heat transfer and an increase in the chemical reaction surface, or a decrease in initiation induction time. Hence, the decreased detonation pressure and temperature (Table 2) should be explained by the increase of the chemical reaction surface and the lowering of the initiation induction time. Moreover, the presence of a carbon additive in the form of MC should shift the oxygen balance towards negative values due to the replacement of hydrogen atoms from FO. In other words, an additional content of carbon monoxide and soot can appear in the post-blast fumes as the result of a negative oxygen balance. These decomposition reaction products should further influence the afterburning effect as secondary reactions that should lead to an increase in detonation pressure [47]. Salzano and Basco have indicated that the afterburning combustion of black powder enables the production level of energy comparable to TNT afterburning energy [47]. The afterburning effect was not included in the ZMWCyw software. Moreover, owing to the specific properties of the MC surface, it is expected that the MC content should influence  $CO_x$  and NO<sub>x</sub> volume in the post-blast fumes, which may humper the afterburning effect.

Parameters	Sample 1	Sample 2	Sample 3
Enthalpy, kJ kg <sup>-1</sup>	-4287	-4269	-4232
Detonation pressure, MPa	2785	2740	2799
Detonation temperature, K	2701	2675	2593
Heat of explosion, kJ kg	4012	3922	3695
Strength of explosion.	976	957	911
Post-blast volume, l kg <sup>-1</sup>	986	977	959
Density, kg m <sup>-1</sup>	823	821	818

Table 2. Average velocity of detonation (VOD) for the investigated samples.

Moreover, based on the potential blasting properties presented in Table 2, it can be observed that the decrease of detonation temperature and pressure was followed by a drop in explosion heat, post-blast volume, and explosive strength. This influence can be explained by the conversion of mass and momentum equations that represent relations between detonation pressure, velocity of detonation, and post-blast volume that further affects the Chapman–Jouguet plain. Furthermore, the Hugoniot's equations indicated an equilibrium state being independent of the explosive density or density of the post-blast fumes, confirming the potential drop of velocity of detonation.

#### 4. Conclusions

In this paper, we presented a possible application of microstructured charcoal in an ANFO explosive.

Based on XRD and IR data, we concluded that adding microstructured charcoal (MC) did not alter the structure of the non-ideal explosive materials. The XRD analysis showed that despite the addition of MC, the sample was characterized by high crystallinity.

SEM analysis indicated that there was no influence of charcoal additives on ANFO morphology. The addition of MC behaved like an inert component in a non-ideal explosive composition (e.g., aluminum in aluminized ANFO). From the MC structure, it can be assumed that other than the presence of FO on the MC surface, FO also experienced macro- and mesoporous absorption. In addition, a small amount of MC powder was visible on the AN-PP. The MC powder was probably obtained due to grinding between prill and MC particles during the mixing process.

All morphology analyses showed that MC may be applied as an ANFO component. The addition of MC to ANFO should influence oxygen balance, density of the non-explosive part, and should eventually result in changes to the Chapman–Jouguet plain.

We evaluated blasted parameters based on the ZMWCyw software, which revealed that the addition of MC decreased the heat of explosion, detonation pressure, and detonation reaction. Moreover, the density of the non-ideal explosive decreased when MC content increased. This ideally should result in a lower velocity of detonation. Despite the fact that the blasting parameters decreased, the differences between the expected blasted parameters of regular ANFO and the studied non-ideal explosive samples were negligible. Moreover, the results obtained from the ZMWCyw simulation should be preliminary treated due to the fact that all simulations concerned non-ideal types of explosives.

The present results could link the improvement of mining explosives by adding a widely available and environmentally friendly additive, such as microstructured charcoal. Moreover, it is expected that the unique surface structure of MC should influence the afterburning effect and the concentration of toxic components in post-blast fumes.

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