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3D concrete printing with wastes for building applications

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3D concrete printing with wastes for building applications

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Abstract: This study focuses on the benefits of deploying plastic waste as a promising alternative to main 3D concrete printing (3DCP) binders. 3D printing technology improvements display that this construction method holds a significant potential by not only finding a globally greener way to developing 3D printing composites but also in researching a more sustainable approach to reducing carbon footprint on the planet, and also becoming one of the possibilities in replacing industrial wastes to ordinary Portland cement. As an alternative to ordinary Portland cement this paper analyses secondary raw materials like burnt shale ashes (BSA), plastic waste (PW) granules and grinded foam rubber (FR). These chosen materials help to solve two environmentally relevant problems: elimination of industrial waste and CO_2 level reduction in concrete production, meantime enhancing the sustainability of the potential 3D printing concrete mixes that had been modified by wastes. Further review presents respective differences between fresh concrete and hardened mix properties. These experimental studies proved that one of four different mixtures significantly enhanced the stability of the studied parameters.

1. Introduction

3D printing is becoming an exceedingly popular building method in today's construction industry. There are more than 110 3D printed structures erected in the last five years [1]. One of the more recent printed residential homes can be found in Wallenhausen and Beckum (Germany), Eindhoven (Netherland), Tempe (Arizona, USA), Richmond (Virginia, USA), Luanda (Angola, Africa). [2, 3, 4, 5, 6].

The 3D printing concrete technology has unlimited potential in terms of material flexibility, savings, labour's cost, design flexibility, and operational agility [7]. Geometry of the 3D-printed constructions varies between orthogonal layouts that replicate existing buildings and spherical shapes that reflect printing capabilities [1].

In 3D printing concrete mixes main binder is ordinary Portland cement (OPC). As known, OPC are produced annually and every tone emits up to 622 kg of carbon dioxide (CO_2) which impacts 5-9% global greenhouse gas (GHS) emissions annually [8, 9]. Despite this, there is an increasing demand in the cement industry factories, developing technologies to reduce CO_2 emissions and produce low carbon concrete (LC2) cement [10]. One of the options is to replace OPC to supplementary cementing materials (SCMs) such as fly ash, silica-fume and slag [11].

As an alternative prospect, one of mentioned SCMs was replaced instead of cement. Waste materials has smaller CO2 emission amount than OPC. This review includes tests and analyzes of variations between OPC and plastic waste. In this research as wastes variated among pozzolanic materials and recycled secondary wastes without molarity of activator solution.

Research perspectives showed that low-carbon housing with 3D printer can be structured in future. Significant advantages of used waste lead to sustainability in the construction industry.

2. Materials and Methods

2.1. Characteristics of the raw materials

Compositional components are selected by evaluating the availability of local secondary materials in the region. For replacement of OPC was widely available pozzolanic material of BSA (Figure 1). Second alternative material is PW granules from local waste buying firm. And third explored material was grinded FR from a Lithuanian foam rubber producer, where this material is as a leftover waste after the production process.

Burnt shale ash used in this research is generated from one of the world's the biggest oil shale energy companies. This artificial material is already being used in the production of aerated autoclaved concrete blocks, in cement and concrete productions and also in dry building materials mixtures, because of its chemical properties [12]. One of the main BSA components is silicon dioxide (SiO^2) about 20-35%. Other elements are calcium oxide (CaO - 2-25%), calcium carbonate ($CaCO_3$ - 1-25 %), anhydrite ($CaSO_4$ - 1-20%), small amounts of aluminum oxide (AL_2O_3), iron oxide (Fe_2O_3), sulfur trioxide (SO_3) and magnesium oxide (MgO – 3-5 %). Particle size determination of BSA is similar to OPC: >0,25 mm – 0,8%; 0,125 mm – 12,2%; 0,09 mm – 45,3%; 0,063 mm – 11,6% and bottom – 30,1% [13].

Figure 1. Burnt shale ash powder.

As an alternative binder plastic waste granules from plastic and electronic waste buying firms were tested (Figure 2). Most plastics are organic polymers, but before recycling these wastes are assorted and then processed mechanically by grinding it from synthetic or semi-synthetic materials or products. One of the negative features of this waste is that it cannot always be homogenous and clean. Potentially, recycling different plastics, PW granules can consist of: high-density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) [14]. Particle size determination of PW granules was more like coarse sand: >2,0 mm – 15,7%, 1,0 mm – 70,2%; 0,5 mm – 12,6% and bottom – 1,4 %. Different granules can generate disparate results to concrete. Despite that, plastic wastes are huge global ecological problem. That is why, it is selected to use in 3D printing concrete modifications.

Figure 2. Plastic waste granules.

In foam rubber (or also called foam plastic) production a lot of products need to be cut in specific shapes, small leftover pieces and foam rubber dust, cannot be used in production afterwards, for example in mattress production (Figure 3). One of the potential forms of reusability is to use it as a filler in toys or seat bags, however the end product does not offer best possible quality. Other solution for reusing these wastes can be passed down to concrete mixes. Particles of FR were sieved through 2 mm sieve, and it has more course particles than fine. Foam rubber usually is produced from polyols and diidocyanates. Further research analyzed various types of polyurethane foam wastes left after production processes.

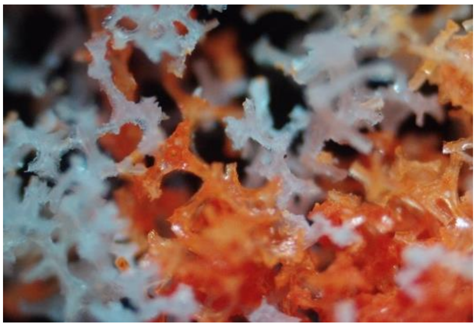


Figure 3. Grinded foam rubber.

In this research field, to replace OPC amount to plastic waste, an already available 3D printing mix composition was used. In this study it was called an etalon mix, starting structure, with only binder - OPC. All waste materials were added to etalon composite mixture by a 10% mass of OPC. Other materials, constant weight, used in composition: calcium hydroxide, accelerator, expansive additive, superplastificator, dispersible polymer powder, polypropylene fiber. All composition materials and weights are added to Table 1.

Table 1. 3D printing mix composition used in research.

Number of compositions	OPC, g	BSA, g	PW granules, g	Grinded FR, g	Sand, g	Other, g
Nr 0	345,0	0	0	0	595,5	59,5
Nr 1	310,0	35,0	0	0	595,5	59,5
Nr 2	310,0	0	35,0	0	595,5	59,5
Nr 3	310,0	0	0	35,0	595,5	59,5

All used materials in research were kept in the same conditions, selected from the same batch, seeking to avoid any deviations. The only adjusted material amount was the OPC with plastic waste. Despite that all, composition had the same weight and were mixed with the same amount of water. Water and composition (W/C) ratio were 0,51.

2.2. Research methods

Most of the tests were conducted according to EN 998-2:2016 standard to mortar mixes. Majority of articles in theme of 3D printing materials use this standard as a base of all tests. Nowadays, some institutions are working in standardization of 3D printing, but until now there is no one harmonized standard for 3D printing mixes. In some cases, 3D printing is associated with Additive Manufacturing (AM) standards, but it can be as a part of a whole harmonized standard. Not only government committees, but also individual companies collaborate together to create this standard [15].

Tests were conducted to compare workability, physical and mechanical properties compositions to measure the differences between them, and evaluate the influence from plastic waste. Main tested properties of fresh mixed composites (Table 2):

- L - consistence of fresh mortar (EN 1015-3:1999);
- M – bulk density of fresh mortar with 1 liter bowl (EN 1015-6:1998);
- O – air content of fresh mortar (EN 1015-7:1998);

For evaluating the hardening process, fresh concrete mix temperatures with thermocouples were measured (Figure 4). Temperature distribution of compositional mixes hardening process was performed using specialized equipment. Fresh mixed concrete was poured into plastic cylinders molds (diameter – 20 mm; height – 70 mm). All cylinders were added into a special chamber from EPS. Thermocouples were immediately inserted into filled cylinders. Then the top of chamber was covered by two layers of EPS plates and pressed with weight. Temperature data was transmitted to special computer set program "PLW Recorder". Values of thermocouples were recorded every minute, with accuracy of temperature – 0,01°C. All compositional mixes were measured in one time for 50 hours [16].

Main hardened composition measured parameters and tests (Table 4):

- Deformation through all first 28 days of hardening process (according to EN 13454-2:2003 for prism 0,16 m length);
- Flexural strength after 28 days (EN 1015-11:2019);
- Compressive strength after 28 days (EN 1015-11:2019);
- Optical microscope analysis (photos after 28 days of hardening);
- Scanning electron microscope analysis (images from samples);
- Energy dispersive spectroscopy spectrum analysis.

3. Results

3.1. Fresh mortar test results

Firstly, all 3D printing compositions were weighted and mixed in dry form. Then, all mixes were stirred with water by hand mixer separately, with the same W/C ratio - 0,51. After 3 minutes concrete were remixed. After that, using a flow table, consistency of fresh concrete was determined (Table 2). The results revealed, that a 5% increase in flowability compared to the etalon (NR 0) in concrete with BSA and PW granules were observed. It is likely because BSA particle are more rounded, generally more spherical, than OPC, it provides better lubricant effect, workability and fluidity. Because PW granules have no absorption of water it also has good flowability. Differently, then others compositional mixes, concrete with grinded FR had a greater increase in water absorption which shows that mortar is very stiff and has twice lover flowability parameter.

Table 2. Parameters of fresh composition mix.

Composition	L, cm	M, kg/m^3	O, %
NR 0	19,4	2100	6,1
NR 1	20,3	2105	5,8
NR 2	20,2	2030	6,8
NR 3	10,0	1800	12,0

After mass measurement it was observed that an almost equal mass between etalon mix and mix with BSA, it possible that it is very familiar to OPC. Other close but smaller mass result was observed with PW granules. Variously than others, mix with light binder contained a lesser mass – grinded FR. Tests with bowl continues by measuring air content in 1 liter mass of concrete. Results determined that the mix with BSA had a slightly better compacting characteristic. From mass result it is seen that it creates a slightly denser structure which can cause an increase in strength and reduce permeability. PW granules displayed that its composition can contain only 10% more air in it that the etalon. As expected, NR 3 mix showed significant increase of air (96%) than etalon which theoretically can affect better frost resistance than other compositions.

For visual evaluation 3D printing concrete mixes were printed in laboratory with caulking gun (Figure 4). Preliminary printings shows that effect of printing was similar between mixes NR0 and NR1. NR2 mix has some issues with printability because of inhomogeneous mixture, mostly it was stuck in nozzle. In Figure 5 could be seen difference between printed concretes. One mix, NR3, was unprintable, because it has stuck in nozzle and did not print at all.

Figure 4. Laboratory 3D printing caulking gun.

A) NR 0

B) NR 1

C) NR 2

Figure 5. Laboratory 3D printing examples.

To compare thermal parameters, temperatures during the hardening time were measured (Figure 6). All measuring process last up to 50 hours, but approximately after 24 hours there was no changes in chart. Figure 4 represents only the peaks of hardening time, but not all measured diagram data.

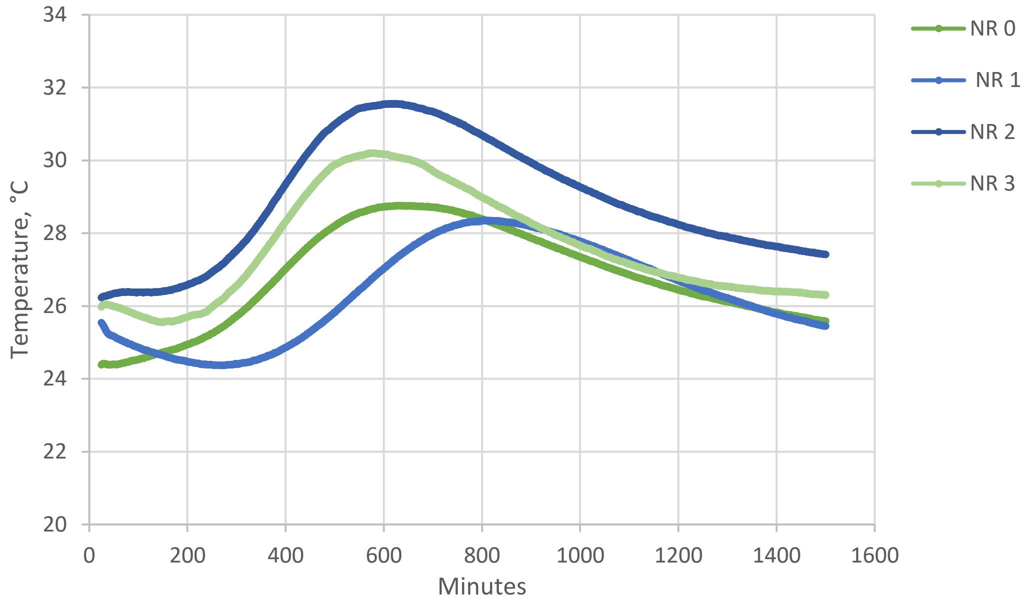


Figure 6. Hardening time temperature diagram.

Exothermic hardening time reaction temperature results are presented in Table 3. From there it can be concluded that fastest reach of highest temperature has NR 2 and NR 3 compositions with PW granules and grinded FR. It could be because in mixes there are 10% less cement than in etalon mix NR 0 and main binder was changed to nonreactive material. But from curve NR 1 can be determined that BSA reacts slower than OPC and emits fairy less exothermic warmth.

Table 3. Compositions hardening time temperature results.

Parameter	Composition name			
	NR 0	NR 1	NR 2	NR 3
T_{max}, °C	28,77	28,35	31,56	30,21
T_{Tmax}, min	624	799	576	576

3.2. Hardened compositions test results

Table 4 presents the average results of hardened composition properties after 28 days of curing according EN 1015-11:2019. Approximately 50-60% lower strength results also can be affected by 5-15% reduced mass and 11-96% increased air amount in compositions. Despite the fact that hardening time reaction pics were reached 48 minutes earlier than others, but 10% reduced amount of OPC gives 50-60% lower strength results. From NR 0 and NR 1 volume density results a hypothesis was reached that the strength of concrete with BSA could be greater than just with OPC in composition. But from results it can be seen that 10% of BSA can lightly enhance flexural strength by 5%, but compressive strength in this case were reduced in 7%. Firstly, it can be as a result of a larger amount of free lime in hydration reaction of OPC combined with BSA. Secondly, analyzing hardening time results also can be traced that for 3 hours slower hydration reaction of BSA could affect reduced compressive strength, because its hardening process is still ongoing [17].

Table 4. Parameters of hardened compositions, after 28 days.

Composition name	Flexural strength, N/mm^2	Compressive strength, N/mm^2	Deformation, mm/m
NR 0	6,6	55,8	-12,88
NR 1	6,9	51,9	-17,88
NR 2	4,8	27,5	-13,81
NR 3	4,5	22,5	-10,50

From deformation measuring results in Figure 7 and Table 4, composition with BSA displayed a significant 40% increase in shrinkage. According to other scientists, increasing BSA amount can affect increased shrinkage [18]. It also can be related to longer BSA hardening time. Further information about not reacted BSA particles is displayed in Figure 9. 19% better than etalon deformation results showed composition NR 3 with grinded FR. It is possible, because of foam rubber property to change their dimensions depending from the load. The most familiar result from NR 0 represented composition NR 2 with PW granules. It is suggested that the feature of plastic granules to not react with other compositional components and be in the same dimensions despite loads. Generally, deformations in NR 2 can be caused from the same influencing factors as NR 0.

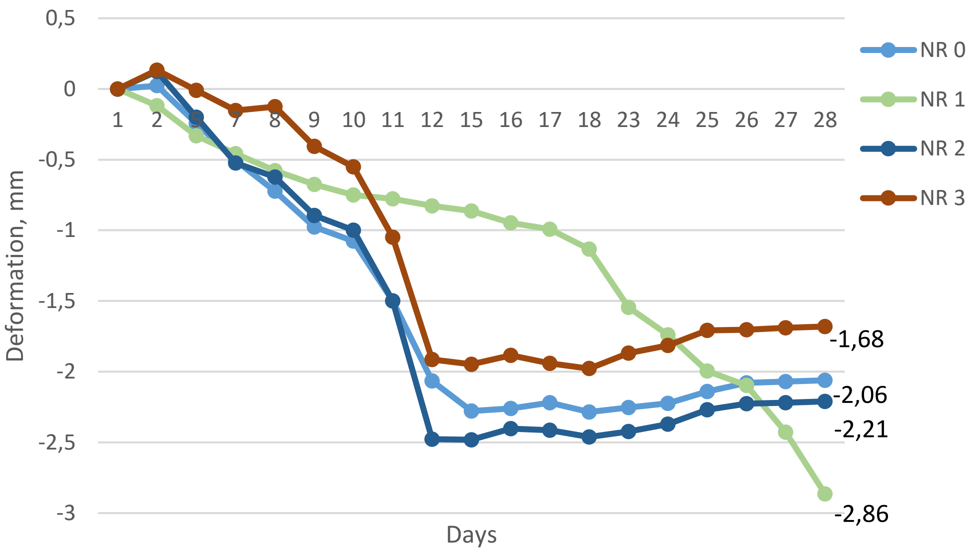


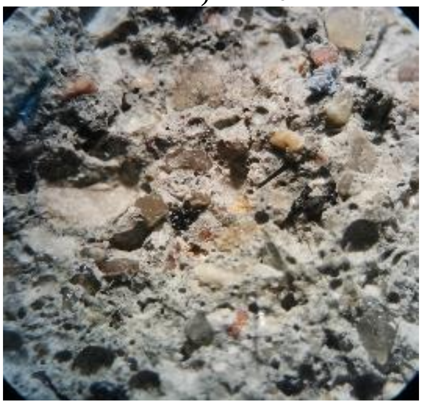
Figure 7. Deformation graph of compositions prisms.

3.3. Hardened compositions microscopy analysis

Photos with optical and scanning electron microscope (SEM) was investigated to the cut of through cross sections of the samples after compressive strength test. Figure 8 presents picture taken after compositional concrete surface observation with optical microscope. In picture A surface of the composite was quite compact. Differently than the latter, Picture B contains a significant number of small pores, in Picture C – voluminous pores. Variously than others in Picture D surface have noticeable changes spongelike structure.

A) NR 0

B) NR 1

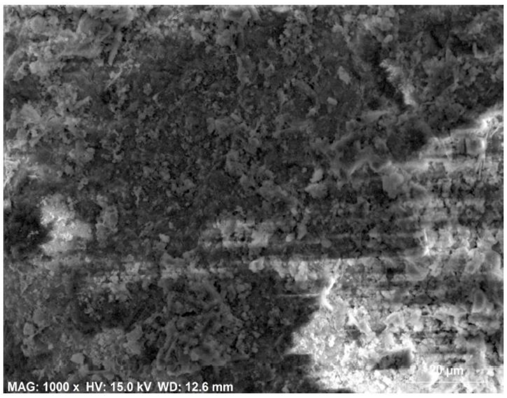


C) NR 2

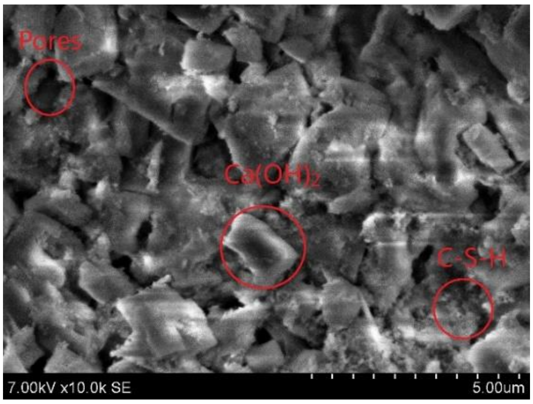
D) NR 3

Figure 8. Hardened compositions photo with optical microscope.

Further test of optical analysis samples of compositions with SEM followed. During the SEM micrographs samples were also explained in EDS specters. In Figure 9 compounds of calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C-S-H) were visible. A image displays a 1000 times zoomed in sample, which later was used for energy dispersive X-ray spectroscopy (EDS).



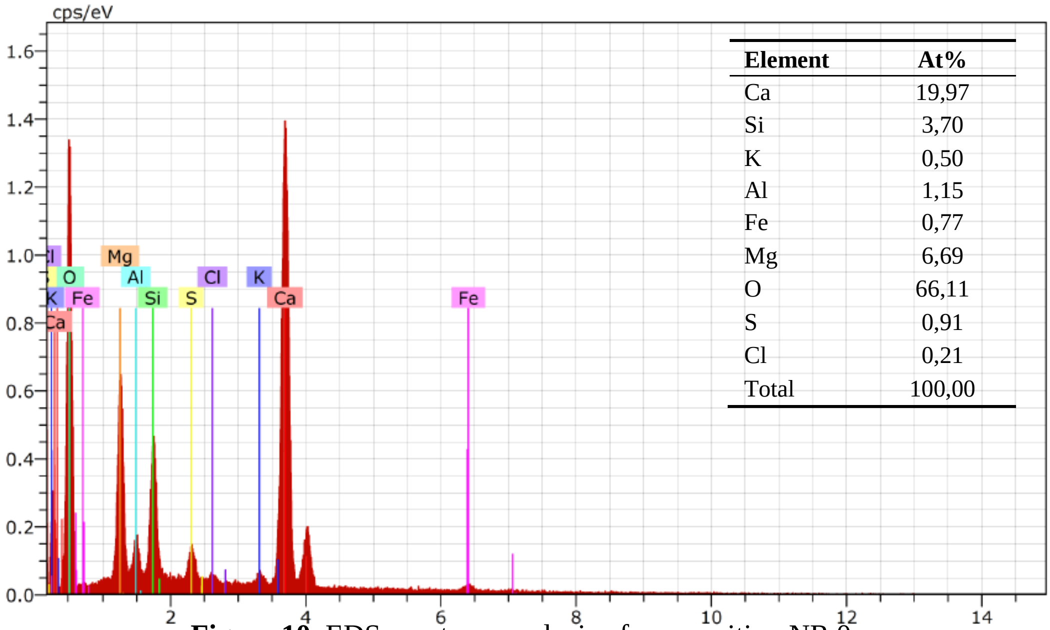
A) x1000



B) x10000

Figure 9. SEM image of composition NR 0.

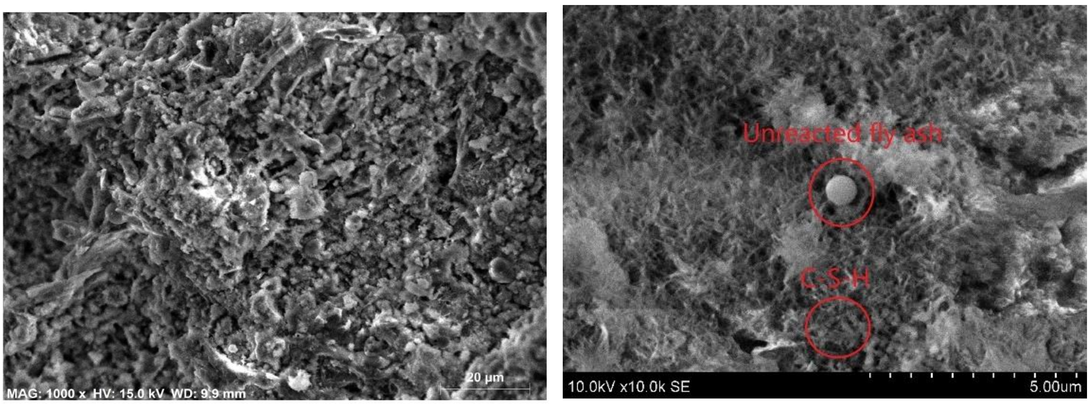
Following this further EDS spectrum analysis in Figure 10 it is seen that the composition NR 0 main elements were oxygen, calcium, magnesium and silicon. Those are the typical elements after OPC initial setting time: C_3A, C_4AF and $2C_2S$.



Element	At%
Ca	19,97
Si	3,70
K	0,50
Al	1,15
Fe	0,77
Mg	6,69
O	66,11
S	0,91
Cl	0,21
Total	100,00

Figure 10. EDS spectrum analysis of composition NR 0.

In the following sample NR 1 SEM image Figure 11 explains why this composition has a smaller compressive strength than expected. Middle of the image contains an unreacted burnt shale ash particle. In Figure 9 A image an unreacted or starting to harden burnt shale ash shell wrapped with C-S-H gel can be observed. The latter image shows an area where EDS spectrum analysis was done (Figure 12). Like in other specters, NR 1 main concrete composition specter elements contain oxygen, calcium and silicon. Elements, specific to BSA, can be found in larger amounts, such as 90% sulfur, 62% silicon, 35% calcium, 31% aluminum.



A) x1000 B) x10000

Figure 11. SEM image of composition NR 1.

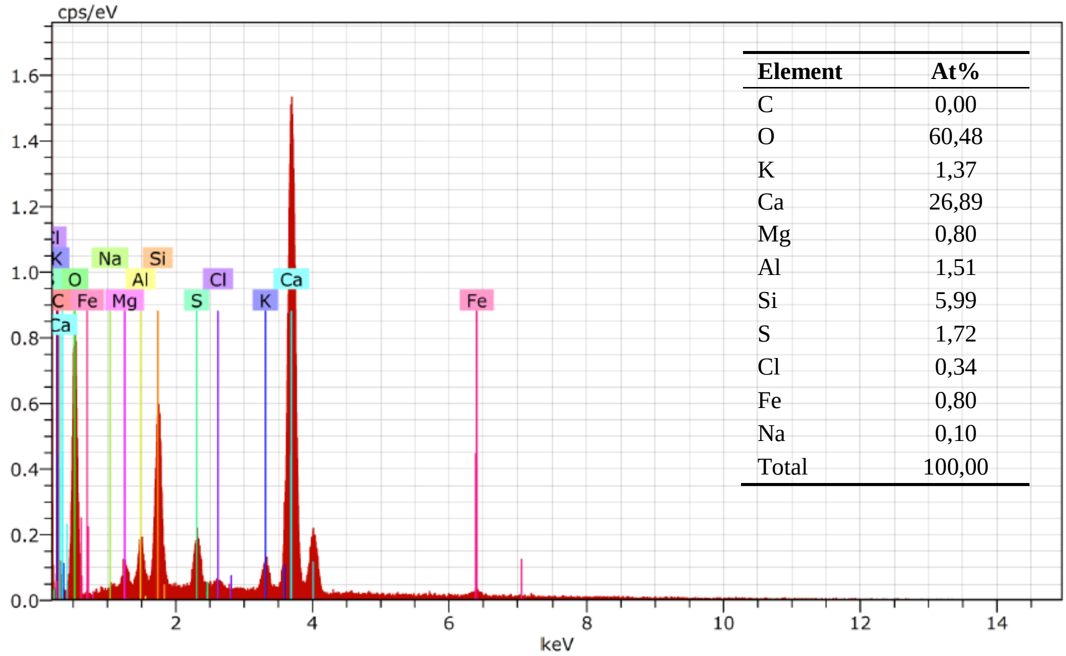
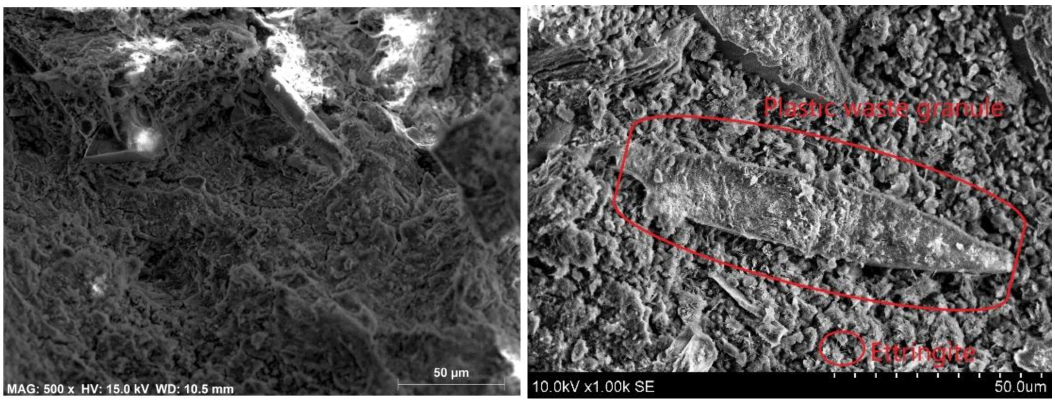


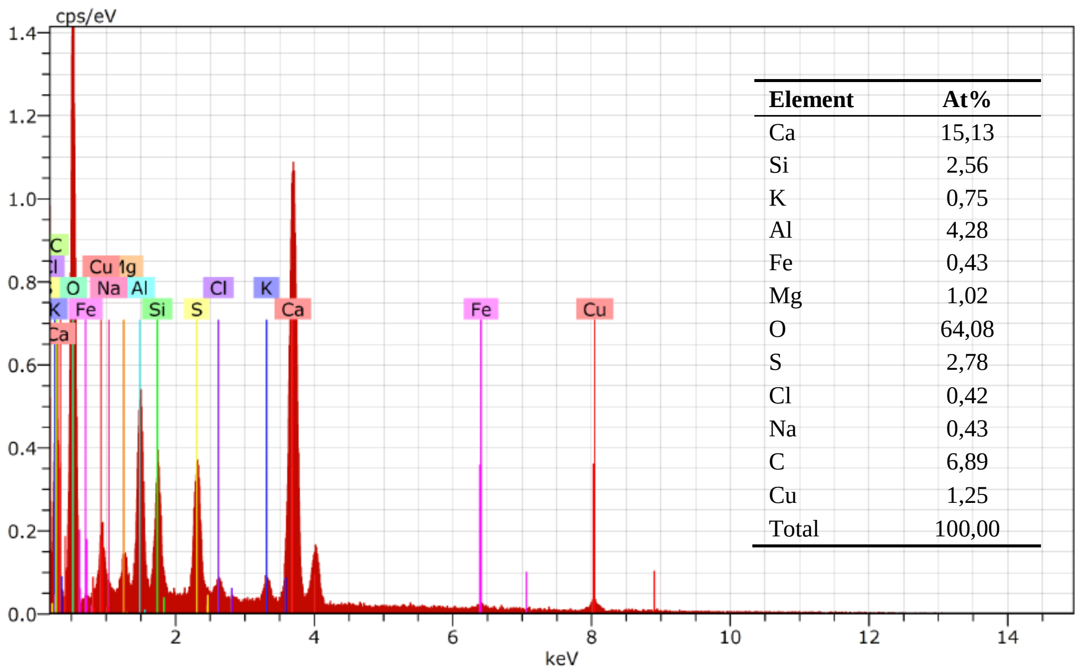
Figure 12. EDS spectrum analysis of composition NR 1.

Results from NR 2 composition SEM analysis shows that in both images plastic particles can be observed (Figure 13). Other concrete hardening products like C-S-H, calcium hydroxide or small spikes of ettringite can also be seen. According to spectrum analysis results of composition NR 2, etalon contained a lower amount of main elements, after the initial setting time (Figure 14). New elements like carbon and coper appear, as they are the main components of plastic granules. Furthermore, because of plastic granules, almost three times larger amounts of aluminum can be seen.



A) x500 B) x10000

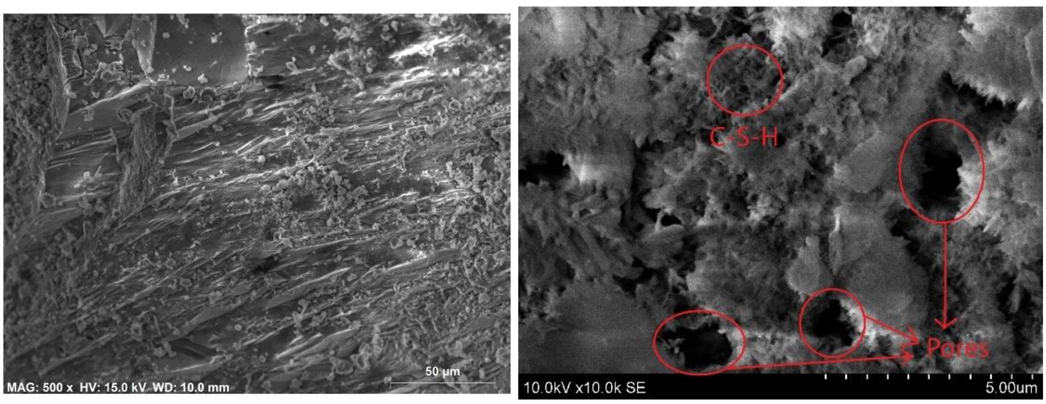
Figure 13. SEM image of composition NR 2.



Element	At%
Ca	15,13
Si	2,56
K	0,75
Al	4,28
Fe	0,43
Mg	1,02
O	64,08
S	2,78
Cl	0,42
Na	0,43
C	6,89
Cu	1,25
Total	100,00

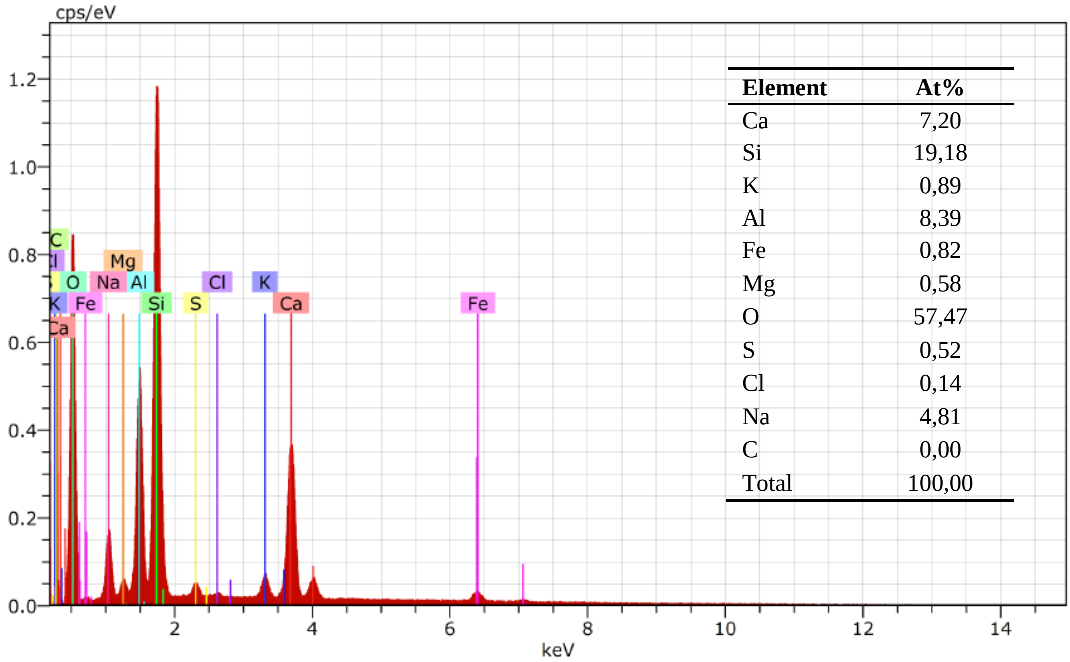
Figure 14. EDS spectrum analysis of composition NR 2.

Final analyzed composition NR 3 shows that in its structure, as expected from air amount in fresh concrete, more pores are seen than in other compositions (Figure 15). Main elements from initial setting time stays the same, only in lower amounts (Figure 16). Differently than in other compositions silicon and aluminum amounts in a specific area are enlarged.



A) x500 B) x10000

Figure. 15. SEM image of composition NR 3.



Element	At%
Ca	7,20
Si	19,18
K	0,89
Al	8,39
Fe	0,82
Mg	0,58
O	57,47
S	0,52
Cl	0,14
Na	4,81
C	0,00
Total	100,00

Figure 16. EDS spectrum analysis of composition NR 3.

4. Conclusions

In conclusion, the research has shown that in finding an alternative binder to 3D printing concrete, which has a possibility to reduce carbon footprint, the most similar material to Portland cement could be burnt shale ashes. As a waste burnt shale ash is a closer analog to Portland cement because they both are reactive materials in concrete composite. This is a reason of the main similarities between compounds NR 0 and NR 1.

Looking in a perspective of finding a solution to eliminate as much industrial wastes as possible, other plastic waste used in concrete composition could be foam rubber wastes. Despite worse workability fact, which can be fixed with supplementary materials, foam rubber shows positive air parameters of fresh mortar to have longer frost resistance than others. Also, quicker than etalon mix hardening time reaction shows that building from this material could save Portland cement. Pursuing this further, strength results were twice lower than the etalon, but for typical 3D printing concrete there is no need to have high-strength. One more advantage of foam rubber compared to burnt shale ashes is that NR 3 composition deformation parameter showed 58% better results than NR 1.

Finally, the research to find favorable solutions in maintaining a cleaner environment with less wastes and reduce the amount of Portland cement in cement mixes used in the construction industry. The results have shown that the most promising solution can be a collaboration of burnt shale ashes and foam rubber as binders in 3D printing concrete in the future.

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