A Review Regarding the Use of Natural and Industrial by-Products in the Production of Geopolymer Binders

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Abstract. Rapid growth in population has led to the generation of large amounts of waste and environmental degradation. Environmental protection for future generations and to preservation of the already limited mineral resources, could be obtained with sustainable solutions for traditional Portland Cement Concrete. In order to produce geopolymers binders, raw materials rich in aluminum and silicon are alkali-activated. Some of the raw materials, for the production of the geopolymer binders can be obtained from natural sources, such as kaolin, metakaolin (calcined kaolin), diatomite, volcanic rock, etc., or industrial waste arising from production processes, such as fly ash, iron slag, blast furnace, granulated blast furnace slag, silica fume, marble dust, etc. The aim of this paper is to present relevant data in the field of alkali-activated geopolymer materials and study the opportunities of using Romanian mineral local raw materials in order to produce these types of binders.

1. Introduction
The problems facing mankind today are related to global warming, caused by the accumulation in the atmosphere of greenhouse gases. Changes in the natural characteristics of the atmosphere, as a result of the actions of physical, chemical, biological agents that manifest a harmful effect on the environment, lead to air pollution. The main pollutants are: carbon monoxide (CO), carbon dioxide (CO₂), sulphur dioxide (SO₂), nitrogen dioxide (NO₂), particulate matter (PM), volatile organic compounds (VOC), benzene and heavy metals. The major sources of CO₂ production, one of the main pollutants, are the production of thermo-electric energy, manufacturing and metallurgical industries.

The construction industry presents the fastest development in the world. According to the statics carried out in recent years, approximately 260,000,000 tonnes of cement are needed annually, in order to satisfy the needs for development [1]. The cement industry is responsible for producing large amounts of CO₂ emissions because, for producing one tonne of Portland cement, about one tonne of CO₂ is released into the atmosphere [2] resulting in high pollution of the environment.

Rapid population growth and urbanisation in developing countries have led to large amounts of solid waste and increased environmental degradation. Around 90-95% of all waste in the world is dumped on open land or warehouses, creating considerable environmental problems. Also, given that the natural reserves are limited, alternative methods of using these types of wastes should be found, by keeping it in optimal parameters and provide the opportunity for future generations to enjoy a clean air and nature.

Management of construction waste, recycling and re-using are key strategies adopted in order to protect natural resources and to prevent environmental pollution, by using waste materials or industrial by-products, and can also contribute to the economy having several other advantages [3, 4]:
• Reducing demand for new resources;
• Reducing energy costs for transport and production;
• Use of waste that would otherwise be lost in landfills;
• Sustainable urban development by conservation of land areas;
• Improving environmental conditions.

An alternative to traditional Portland cement concrete could be offered by Geopolymer concrete, which does not use Portland cement, and could provide significant environmental benefits. Geopolymers are a subclass of alkali-activated materials. The usual geopolymer materials mixture includes fly ash, alkaline activators, mineral additives and aggregates (Figure 1).

Figure 1. Schematic representation of a compositional Geopolymer Concrete.

The term geopolymer was originally introduced by Davidovits, in 1991 [5], representing a wide range of inorganic materials. According to him, among the nine different classes of geopolymers, Geopolymer concrete is of particular interest, consisting of aluminosilicate materials that could be used to completely replace traditional Portland cement concrete [6].

This class of geopolymers is also called alkali-activated cement or inorganic polymer cement, which is produced by dissolving thermally activated natural materials such as kaolinites clay, fly ash or slag in an alkaline activation solution to provide a source of silicon (and) and aluminium (Al), generating the polymerisation process. Inorganic molecular chains and networks are then created and a hardened binder is obtained [7, 8].

In short, since the geopolymerization reaction occurs when the alumino-silicates contained in the raw material react with a strong alkaline solution, any material containing silicon and aluminum can be used in the production of geopolymer materials [5-9].
2. Producing geopolymer concrete with different raw materials

Minerals containing aluminum and silicon can be found everywhere especially as by-products. Therefore, the production of geopolymer concrete is not only an alternative to recycle a large amount of waste, but also to produce concrete with special properties, such as very good compressive strength from an early age, good fire and aggressive environment resistance, etc. The multitude of raw materials that can be used in the production of alkali-activated geopolymer materials has been intensively studied and three main categories were established based on their origin: industrial waste (IW), general waste and recycled materials (GWRM) and natural materials (NM) [10].

2.1. Industrial waste (IW) used as raw material

Worldwide huge demand for services and products leads to large quantities of industrial waste and by-products such as coal-fired combustion ash, metallurgical slag, mine waste or agricultural waste [11], most of them being stored or dumped on the ground in landfills. Partial use of the total amount of waste generated is already being used in civil engineering industry in order to improve concrete properties [12, 13], but most of it is not capitalized.

2.1.1. Fly ash (FA). Since 1930, the term fly ash was used in the industry, with research on the possibility of using this type of by-product in concrete starting in 1937, where Davis and his colleagues from the University of California presented this possibility. Research showed in 1956 that parts of Portland cement in concrete could be replaced by fly ash with no effects on the mechanical properties [14]. Worldwide production of fly ash is increasing (Figure 2) since energy demand for population is rising, but the quality of this type of waste should also increase, as the amount of fly ash with a low content of L.O.I. (Loss on Ignition) available on the market is continuously decreasing [15, 16].

As seen in Figure 2, fly ash production increased in countries such as India, China and the U.K. in 2013, but declined in the U.S., when compared to 2008. Simultaneously with the increase in production, in India, China and the U.K., the use of fly ash in different fields has also increased. In countries such as Denmark, Italy and the Netherlands, the re-use of ash production is 100%, which shows that a complete reintegration into the circular economy concept of this type of industrial waste can be achieved (Figure 3). Due to the total re-use there are no slag dumps that would lead to environmental pollution.

![Figure 2. Production of fly ash in different countries (million tons per year) [15].](image1.png)

![Figure 3. Percentage use of thermal power plant ash in different countries [15].](image2.png)

Usually, fly ash is used as main binding material for the production of alkali-activated materials. Due to its chemical composition, careful consideration is needed when using this type of waste and certain properties should be taken into consideration [16]. Together with the alkaline activator (liquid part), fly ash (solid) represents the main constituents of the geopolymer binder [17]. Therefore, in the production of alkali-activated fly ash-based geopolymers, two types of fly ash are generally used, with specific ranges of chemical compounds (Table 1).
Table 1. Chemical composition typical fly ash [18].

| Component | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | K$_2$O | Na$_2$O | SO$_3$ | LOI | TiO$_2$ |
|-----------|---------|-------------|-------------|-----|-----|--------|--------|--------|-----|---------|
| Class C-  |         |             |             |     |     |        |        |        |     |         |
| Percentage wt% | 15-45   | 20-25       | 4-15        | 15-40 | 3-10 | 0-4    | 0-6    | 0-10   | 0-5 | <1       |
| Class F-  |         |             |             |     |     |        |        |        |     |         |
| Percentage wt% | 20-60   | 5-35        | 6-24        | 1-12 | 0-5  | 0-3    | 0-4    | 0-4    | 0-15| 1-2      |

2.1.2. Granulated blast furnace slag (GBFS). Granulated blast furnace slag is a byproduct of the iron manufacturing process, obtained by extinguishing molten slag from the furnace with water. The removal of such large quantities of slag is a major concern and problem for steel producers. Clay is produced by the action of various flows on the materials of iron ore during the process of manufacturing iron and steel. Slag produced at the furnace (BF) during the manufacture of iron is called slag furnace. Slag produced by steel smelting is known as steel slag. First of all, slag is formed from calcium, magnesium, manganese and aluminum silicates in various combinations together with iron oxide. The main difference between furnace slag and steel slag are the iron content. Typical mixtures of alkali-activated geopolymer materials produced using GBFS were reported by Shekhawat and the typical chemical composition of the GBFS used in his studies are presented in Table 2 [19].

Table 2. Chemical composition of GBFS- granulated blast furnace slag [19].

| Component | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | Loss on ignition |
|-----------|---------|-------------|-------------|-----|-----|------------------|
| Percentage wt% | 32.97   | 17.97       | 0.72        | 35.08 | 10.31 | 0.58             |

2.1.3. Marble Dust (MD). Marble dust, obtained by processing marble slabs, is a mineral addition that can be used successfully to produce environmentally friendly concrete based on mineral binders, alkali-activated. Compressive strength of geopolymers containing marble dust and granulated blast furnace slag in different compositions are shown in Figure 4 [20].

Figure 4. Effect of MD / BFS ratio on alkali-activated geopolymer materials compressive strength (M5S5=MD50%+BFS50%, M6S4=MD60%+BFS40%, M7S3= MD70%+BFS30%) [20].
As seen in Figure 4, increasing the percentage of marble dust (MD), at an early age of 7 days, compressive strength decreases. Therefore, if it is desired to obtain high compressive strength values at 7 days, it is indicated that the percentage of marble dust (MD) to be reduced. At the age of more than 7 days, an evolution of this parameter cannot be assessed by a simple percentage analysis.

2.2. General waste and recycled materials used as raw materials (GWRM)

General waste or recycled materials are produced all over the world. Although these types of raw materials represent a much smaller quantity than industrial waste, the conversion of added value is of great research interest. Some of the general waste used in the production of alkali-activated materials are ash from waste paper sludge (WPSA) and construction wastes.

2.2.1. Construction waste (CDW). Construction and demolition waste are limited in use, mainly used as fillings, as well as separately in recyclable materials. One of the promising technologies, geopolymerization, can be used to fully use construction and demolition waste.

Increased attention is required when re-using of CDW as materials for alkali-activated geopolymer production. Cities are becoming larger, therefore almost no land is available for disposal / storage in urban areas. Most of the CDW (Figure 5), about 70% is fly ash, sand cement mixture from demolition (includes hydrated cement and sand), cement concrete and sand mixture (includes hydrated cement, sand, aggregate, etc.), brick, sandstone, etc. and the remaining 30% includes wood, metals, plastics, glass, etc. [4].

![Figure 5. CDW before and after milling a)concrete and b)fired clay [4].](image)

2.3. Raw natural materials (NM)

Natural source raw materials can be also used in the production of alkali-activated geopolymer materials: kaolin (kaolinite), metakaolin (calcined kaolin), feldspar, sandy clay, diatomite, puzazzolic volcanic rocks, etc.. The main barrier when using these types of materials is the limitation to certain geological areas and also limited quantities.

2.3.1. Metakaolin (MK). MK is obtained by calcination of kaolinous clays in furnaces at temperatures of about 500-800°C. Kaolin can be obtained directly by excavating natural deposits, or it can be obtained as a component of decanting waste from the mining industry [21].

2.3.2. Other clays. In addition to metakaolin, heat-treated clays rich in muscovite, obtained from tungsten mine waste (TMW), were used as alkaline activators in Portugal [22, 23].

2.3.3. Feldspar. Given that it is mostly the Earth's crust, being rich in silicon and aluminum, in approximately equal proportions, it is an important source of alkaline activator that can be used to produce geopolymer materials.

2.4. Summary of waste materials with potential use as raw materials for geopolymer production

Some of the raw materials used in literature in order to produce alkali-activated geopolymer materials are presented in Table 3, by analyzing their chemical composition and studying their capacity to provide sources of silicon (Si) and aluminium (Al), which later generate the geopolymerization process [24-41].
| Materials                          | SiO<sub>2</sub> | Al<sub>2</sub>O<sub>3</sub> | Fe<sub>2</sub>O<sub>3</sub> | CaO  | MgO  | Na<sub>2</sub>O | K<sub>2</sub>O | SO<sub>3</sub> | FeO  |
|-----------------------------------|----------------|-----------------|---------------|------|------|-------------|-----------|----------|------|
| **Industrial waste**              |                |                 |               |      |      |             |           |          |      |
| Low calcium fly ash (LFA)         | 50.00          | 28.25           | 13.50         | 1.79 | 0.89 | 0.32        | 0.46      | 0.38     | -    |
| High calcium fly ash (HFA)        | 39.70          | 20.00           | 14.10         | 17.30| 1.40 | 1.40        | 2.70      | 2.60     | -    |
| Granulated Blast Furnace Slag (GBFS) | 32.46        | 14.30           | 0.61          | 43.10| 3.94 | 0.24        | 0.33      | 4.58     | -    |
| Silica Fume (SF)                  | 92.00          | 0.46            | 1.60          | 0.29 | 0.28 | 0.51        | 0.61      | 0.19     | -    |
| Steel Slag (SS)                   | 15.00          | 6.70            | 15.40         | 44.20| 10.9 | 0.20        | 0.10      | 0.70     | -    |
| Vanadium mine tailing (VMT)       | 64.2           | 10.27           | 4.98          | 4.46 | -    | 5.27        | 2.06      | -        | -    |
| Ferronickel Slag (FS)             | 32.74          | 8.32            | 0.76          | -    | 2.76 | -           | -         | -        | 38.8 |
| Tungsten mine waste (TMW)         | 53.48          | 16.66           | 12.33         | -    | 1.27 | 0.62        | 7.65      | -        | -    |
| Cement Kiln Dust (CKD)            | 11.00          | 3.90            | 2.00          | 42.00| 3.60 | -           | 0.60      | -        | -    |
| Waste paper sludge ash (WPSA)     | 26.25          | 17.50           | 4.40          | 23.40| 0.90 | 0.10        | 0.20      | 4.63     | -    |
| Water Sludge (WS)                 | 70.40          | 15.40           | 5.30          | 1.53 | 0.96 | 0.90        | 3.66      | 0.31     | -    |
| **General waste and recycling materials** |            |                 |               |      |      |             |           |          |      |
| Demolished Wall (DW)              | 76.42          | 1.88            | 1.28          | 9.84 | 0.26 | 0.22        | 0.08      | 2.09     | -    |
| Waste concrete (WC)               | 71.53          | 2.14            | 2.43          | 12.76| 0.39 | 1.04        | 1.13      | 0.33     | -    |
| Waste glass (WG)                  | 72.5           | 0.40            | 0.20          | 9.70 | 3.30 | 13.7        | 0.10      | -        | -    |
| Ceramic waste-red clay brick (CW-RCB) | 50.95        | 16.92           | 6.68          | 9.92 | 5.62 | 0.55        | 4.33      | 3.37     | -    |
| **Natural materials**             |                |                 |               |      |      |             |           |          |      |
| Metakaolin (MK)                   | 54.78          | 40.42           | 0.76          | 0.10 | 0.41 | 0.07        | 2.72      | -        | -    |
| Kaolin (K)                        | 48.10          | 36.90           | 0.26          | 0.20 | 0.17 | 0.20        | 1.90      | -        | -    |
| Silty Clay (SK)                   | 20.10          | 7.55            | 32.89         | 26.15| 0.47 | -           | 3.17      | 4.92     | -    |
| Diatomite (D)                     | 59.30          | 10.00           | 18.50         | 1.20 | -    | -           | -         | 2.74     | -    |
| Volcanic Mud (VM)                 | 38.50          | 14.20           | 23.76         | 5.62 | -    | -           | 4.31      | 0.78     | -    |
2.5. **Summary of compressive strength values of geopolymer by prime materials**

| Type | Prime materials (%wt) | Additives (%wt) | Si/Al Ratio | Type | Compression MPa/Aged | Alkaline Materials |
|------|------------------------|-----------------|-------------|------|----------------------|--------------------|
| IW   | FA class F (90)        | -               | 2.12        | Paste| 95.0/28              | NaOH+Na₂SiO₃      |
| IW   | TMW(90)                | CaOH₂(10)       | 3.20        | Paste| 75.0/56              | NaOH+Na₂SiO₃      |
| IW   | FA(80)                 | Water Sludge(20)| 2.53        | Paste| 70.6/90              | -                  |
| GW   | Ceramic waste-red clay brick | -               | -           | Paste| 71.1/28              | NaOH+KOH          |
| IW   | FA class F (90)        | BA(10)          | 2.32        | Paste| 70.0/28              | KOH+K₂SiO₃        |
| IW   | GBFS(100)              |                | 3.70        | Paste| 67.0/28              | NaOH              |
| NM   | MK(100)                |                | 1.40        | Paste| 65.0/28              | NaOH+Na₂SiO₃      |
| NM   | Natural Pozzolan(100)  |                | 3.44        | Paste| 63.0/28              | NaOH+Na₂SiO₃      |
| IW   | Vanadium(70)           | FA(30)          | -           | Paste| 55.0/7               | NaOH              |
| NM   | MK(80)                 | Steel Slag(20)  | 1.71        | Paste| 44.5/28              | NaOH+Na₂SiO₃      |
| IW   | FA class F (95)        | Silica Fume(5)  | 1.87        | Mortar| 35.0/28              | NaOH+Na₂SiO₃      |
| NM   | Diatomite(100)         |                | 5.93        | Paste| 28.4/28              | NaOH+Na₂SiO₃      |
| NM   | Kaolinite(100)         |                | 1.30        | Paste| 28.0/28              | NaOH+Na₂SiO₃      |
| GW   | Construction waste (70)| MK(20)+CaOH₂(10)| 38.00     | Paste| 26.1/7               | NaOH+Na₂SiO₃      |
| IW   | GBFS(75)               | CKD(25)         | 3.70        | Paste| 24.0/28              | NaOH              |
| GW   | Glass waste(95)        | Metakaolin (5)  | -           | Mortar| 22.0/28              | NaOH              |
| GW   | Waste Paper Sludge(100)|                | 1.84        | Concr.| 17.5/28              | NaOH+Na₂SiO₃      |
| IW   | Ferronickel Slug (100) |                | 4.13        | Paste| 15.8/28              | NaOH+Na₂SiO₃      |
| IW   | Cooper mine tailing (100)|               | 9.29        | Paste| 15.0/7               | NaOH+Na₂SiO₃      |
| NM   | Silty Clay(75)         | FA(25)          | 2.50        | Paste| 14.0/28              | NaOH+Na₂SiO₃      |

**3. Conclusions**

Recycling waste and reducing greenhouse emissions are two of the main goals industry has to improve in order to obtain sustainable and durable development and one viable method can be provided by producing alkali-activated geopolymer materials [48]. As presented above, there is a wide range of waste or by-products that can become raw materials in the geopolymer production through alkali-activation [49].
Replacing Ordinary Portland Cement, in creating binders without clinker, by using industrial raw materials, such as fly ash or granulated furnace slag could reduce or even stop associated environmental problems.

However, careful attention is needed when mineral materials are used for geopolymer production. The variability in terms of physical and chemical properties of these materials should be very well studied. On the other hand, their local availability is also an important parameter in terms of potential environmental benefits, with possible additional costs if the source materials are transported over long distances [50-54].

4. References
[1] Abdul Aleem M I and Arumairaj P D 2012 IJESET 1(2) 118–22
[2] Davidovits J 1994 ACI SP 144 383–97
[3] Kartam N, Al-Mutairi N, Al-Ghusain I and Al-Humoud J 2004 J. Waste Manag. 24(10) 1049–59
[4] Patak A 2016 A laboratory scale synthesis of geopolymer from construction wastes (Tribhuvan: Tribhuvan University, Nepal)
[5] Davidovits J 1991 J. Therm. Anal. Calorim. 37(8) 1633–56
[6] Davidovits J 2005 Geopolymer, Green Chemistry and Sustainable Development Solutions: Proceedings of the World Congress Geopolymer 2005 (France: Geopolymer Institute)
[7] Lăzărescu A, Szilagyi H, Baeră C, Ioani A 2017 IOP Conf. Ser.: Mater. Sci. Eng. 209 012064
[8] Nematollahi B 2017 Alternative binder for fiber-reinforced Strain Hardening Composites (Hawthorn: University of Technology Hawthorn, Australia)
[9] Lăzărescu A, Szilagyi H, Ioani A, Baeră C 2018 IOP Conf. Ser.: Mater. Sci. Eng. 374 012035
[10] Suwan T 2016 Development of self-cured geopolymer cement (London: Brunel University London, UK)
[11] Sujatha T, Kannapiran K and Nagan S 2012 Asian J. Civ. Eng. 13(5) 635–46
[12] Komnitsas K, Zaharaki D and Perdikatsis V 2004 J. Mater. Sci. 42(9) 3073–82
[13] Nuruddin M, Qazi S, Kubiantoro A and Shafiq N 2011 Proc. Inst. of Civ. Eng.-Constr. Mat. 164(6) 315–27
[14] Joshi R C and Lohtia R P 1997 Fly Ash in Concrete: Production, Properties and Uses (Amsterdam: Overseas Publishers Association)
[15] Dhadse S, Kumari P and Bhagia L J 2008 J. Sci. Ind. Res. India 67 11–18
[16] Lăzărescu A, Szilagyi H, Baeră C and Hegyi A 2020 Alternative concrete – Geopolymer Concrete. Emerging Research and Opportunities (Cluj-Napoca: Napoca Star Press)
[17] Bilodeau A and Malhotra V M 2000 ACI Mater. J. 97(1) 41–48
[18] Christy F C and Tensing D 2010 Asian J. Civ. Eng. 12 87–105
[19] Lăzărescu A, Mircea C, Szilagyi H and Baeră C 2019 MATEC Web of Conf. 289 11001
[20] Cheng T W, Ding Y C, Lee W H and Lu P C 2017 MATEC Web of Conf. 97 01004
[21] Lăzărescu A, Szilagyi H, Baeră C, Ioani A and Mircea A. C. 2018 Constr. 19(1/2) 19–25
[22] Pacheco-Torgal F, Castro-Gomes J and Jalali S 2008 Constr. Build. Mater. 22(9) 1939–49
[23] Pacheco-Torgal F, Castro-Gomes J and Jalali S 2009 Constr. Build. Mater. 23(1) 200–09
[24] Hooton R D 2008 Cem. Concr. Res. 38(2) 247–258
[25] Rattanasuk U, Pankhet K and Chindaprasirt P 2011 Int. J. Min. Met. Mater. 18(3) 364–69
[26] Dutta D, Thokchom S, Ghosh P and Ghosh S 2010 J. Eng. Appl. Sci. 5(10) 74–79
[27] Hu S, Wang H, Zhang G and Ding Q, 2008 Cem. Concr. Compos. 30(3) 239–44
[28] Jiao X, Zhang Y and Chen T 2013 Constr. Build. Mater. 38 43–47
[29] Komnitsas K and Zaharaki D 2007 Miner. Eng. 20(14) 1261–77
[30] Pacheco-Torgal F, Castro-Gomes J and Jalali S 2007 Int. Conf. Alkali Activated Materials- Research, Production and Utilization 693–710
[31] Khater H 2012 Int. J. Civ. Struct. Eng. Res. 2(3) 740
[32] Anuar K, Ridzuan A and Ismail S 2011 *IJCEE* **11**(1) 59–62
[33] Kongkaew B 2007 *Sludge-Based Geopolymer* (Bangkok: Kasetsart University)
[34] Khater H 2011 *J. Mater. Civil. Eng.* **24**(1) 92–101
[35] Pascual A B, Tohoue Tognonvi M and Tagnit-Hamou A 2014 *Int. J. Res. Appl. Sci. Eng. Technol.* **3**(13) 15–19
[36] Reig L, Tashima M M, Soriano L, Borrachero M V, Monzó J, and Payá J 2013 *Waste Biomass Valori.* **4** 729–36
[37] Yip C, Lukey G. and Van Deventer J 2005 *Cem. Con. Res.* **35**(9) 1688–97
[38] Hounsi A, Lecomte-Nana G, Djetéli G and Blanchart P 2013 *Constr. Build. Mater.* **42** 105–13
[39] Sukmak P, Horpibulsuk S and Shen S 2013 *Constr. Build. Mater.* **40** 566–74
[40] Phoo-Ngernkham T and Sinsiri T 2011 *KKU Eng. J.* **38**(1) 11–26
[41] Al Bakri A, Rafiza A R, Hardjito D, Kamarudin H and Niza I K 2012 *Adv. Mat. Res.* **548** 82–6
[42] Fernández-Jiménez A, García-Lodeiro I and Palomo A 2007 *J. Mater. Sci.* **42**(9) 3055–65
[43] Sun Z, Cui H, An H, Tao D, Xu Y, Zhai J and Li Q 2013 *Constr. Build. Mater.* **49** 281–27
[44] Hardjito D and Fung S 2010 *Mod. Appl. Sci.* **4**(1) 44–52
[45] Wang H, Li H and Yan F 2005 *Colloids Surf. A Physicochem. Eng. Asp.* **268**(1) 1–6
[46] Allahverdi A, Mehrpour K and Kani E, 2008. *Int. J. Eng. Sci.* **19**(3) 1–5
[47] Ahmari S and Zhang L 2012 *Constr. Build. Mater.* **29** 323–31
[48] Allahverdi A and Najafi Kani E 2008 *Int. J. Civ. Eng.* **7**(3) 154–60
[49] Akcaozoğlu S and Ulu C 2014 *Constr. Build. Mater.* **58** 31–7
[50] Mathew B, Sudhakar M and Natarajan C 2013 *IJCER* **3**(1) 207–12
[51] McLellan B C, Williams R P, Lay J, van Riessen A and Corder G D 2011 *J. Clean. Prod.* **19** 1080–90
[52] Burduhos Nergis D D, Abdullah M M A B, Sandu A V and Vizureanu P 2020 *Materials* **13**(2) 343
[53] Burduhos Nergis D D, Vizureanu P and Corbu O 2019 *Revista de chimie* **70**(4) 1262-1267
[54] Scripcariu L, Mătăsăru D, Diaconescu V 2017 *UPB Scientific Bulletin Series C-Engineering and Computer Science* **73**(3) 83-92