Impurities of recycled concrete aggregate - types, origin and influence on the concrete strength parameters

Justyna Jaskowska-Lemanska

1AGH University of Science and Technology, Department of Geomechanics, Civil Engineering and Geotechnics, al. Mickiewicza 30, 30-059 Cracow, Poland
lemanska@agh.edu.pl

Abstract. Current development megatrends are aimed at finding a balance between the economy, social and environmental aspects. It is also required that the economic processes that are undertaken should be highly effective in these three dimensions. Both the finite amount of the natural resources and the need to manage the construction and demolition waste, while the constant demand for the concrete mix, makes it necessary to develop knowledge and practice in the field of concrete recycling. One of the main issues in the recovery of concrete aggregate is the presence of impurities. Aggregate treatment is a possible solution, but these are energy consuming and costly processes. Therefore, there is a need to estimate their impact on concrete parameters. Such knowledge is necessary for assessing the need for additional aggregate treatment processes. Harmful aggregate impurities are materials that hinder the curing of the concrete, reduce its strength and tightness, cause splinters, violate the anti-corrosion protection of reinforcement. The paper analyses the type of impurities in RCA, as well as its sources and their influence on the technical parameters of the concrete. Six concrete mixes with the same content of coarse aggregate and water-cement ratio were prepared for the research. The first mix contained only natural aggregates, while the second mix was replaced in half by recycled aggregates. In subsequent samples, the recycled aggregate in 5% by volume was successively replaced with: glass, brick, foamed polystyrene and a mixture of these impurities. Both impurities and the recycled aggregate were prepared in 2/8mm fractions. The obtained results were compared to the results presented in the literature.

1. Introduction
Social and economic development and a significant increase in consumption of aggregates in the construction industry make it necessary to seek sources of aggregates other than natural ones. For environmental, economic as well as social reasons, the use of aggregates from industrial waste or recycled construction materials becomes an attractive solution. Aggregates from the recycling of construction waste seem to be the most beneficial solution for both economic and environmental reasons. However, when estimating costs, one should take into account an increase in financial outlays during the demolition of the facility and processing of demolished material. The process of crushing the material in order to obtain appropriate fractions and the selection of pollutants is characterized by high energy consumption. Therefore, research should be carried out in order to extend the range of use of recycled aggregate subjected to less rigorous purification processes. For this purpose, the impact of particular pollutants on the concrete parameters, depending on their quantitative and qualitative values, should be precisely identified. In this respect, it seems utterly important to determine the qualitative and quantitative aspects of typical contaminants in construction rubble. The use of recycled aggregate
should become a common practice, which does not evoke any doubts and, consequently, does not raise objections from engineers and investors in the implementation of "recycled" material to be used for the construction of a new element or a construction object [1].

2. Literature Review

Concrete is a composite made of cement, water, aggregates, mineral additives and chemical admixtures. The role of cement and water, i.e. cement slurry, through their mutual chemical reaction is to join the aggregates to form a solid body. The properties of the aggregate or cement slurry itself are not the same as their resultant properties in concrete. The final assessment of the viability of the aggregate can be achieved on the basis of a combined examination of the component and the composite. The situation does not change in the case of using recycled aggregate, the concrete becomes even more complex composite. The decisive factor determining the parameters of concrete strength on recycled aggregate is the contact quality of the old and new concrete matrix [2], the type and proportion of aggregate pollution also have a significant impact on the decrease in concrete strength. The technical parameters of concrete based on recycled aggregate are difficult to estimate at the design phase - it is possible only in the case of conventional concrete. The current state of the matter is decisively influenced by a wide range of technical parameters of recycled aggregate, which is a resultant of the quantity and quality of mortar, original aggregate and impurities.

2.1 Management of natural and recycled aggregates

Recycled aggregate is derived from the construction waste obtained by the demolition of a building and its crushing and subsequent cleaning. Already at the stage of investment planning, the selection of materials, which will be used to construct the building, will depend on the possibilities of its reuse. Multi-criteria analysis of material selection should take into account the cost of material in the whole life cycle assessment (LCA) [3]. Cheap materials in production may ultimately turn out to be very expensive in processing operations in order to recover their value, both in economic terms, as well as due to the environmental impact, e.g. CO₂ emissions and energy consumption. The cost of concrete production is high and results in high carbon dioxide emissions [4], but its durability and reusability justify its ultimate low environmental impact through the minor need for processing, as well as reducing the necessity of extracting natural resources. The demolition of a building is a crucial stage in its life cycle from a recycling point of view. The selection of demolition technologies and the quality of the selective manual collection of waste will determine the quality of dismantled rubble - in other words, its purity. Attention to the quality of concrete rubble, which is the starting material for obtaining aggregates from recycling, should be initiated already on the construction site. The selective collection should be based on an effective waste management plan, which should include [5,6]:

- analysis of construction processes from the perspective of waste generation,
- classification of waste according to the law,
- method of segregation,
- the method of local storage,
- multi-variant and multi-criteria analysis of waste management,
- schedule of waste management processes.

The quality of the segregation works within the construction site has a significant influence on the degree of contamination of the assortment. As a result, it will determine the potential of the material as a secondary material. In terms of transforming waste into a product, it is important to obtain a product of sufficient quality for further use. In concrete recycling processes, the quality of the construction product is correlated with the purity of concrete rubble to be recycled and with the selected recycling technology. New methods and expanding the knowledge in the field of concrete recycling should contribute to the increase in the effectiveness of their management processes.
2.2 Requirements for concrete aggregates

The standards define recycled aggregate as aggregate, which is a product of the treatment of non-organic material previously used in construction. Currently, the conviction has been established that the requirements for recycled aggregates should be the same as the requirements for natural aggregates [7].

The basic components of recycled aggregate should be original aggregate and mortar. However, harmful contaminants may be present in recycled aggregate. This means that materials which impair the binding and hardening of concrete, reduce the strength and tightness of concrete, cause chipping or affect the anticorrosion protection of reinforcement. These impurities can be divided into physical and chemical contaminants. Table 1 shows the types of impurities included in the standards depending on aggregate size and their acceptable content for all aggregates used in concrete. These contaminants may originate from the place of aggregate extraction or the place and conditions of its storage.

| Type of impurities | particle size | Permissible mass concentration / Notes |
|--------------------|---------------|----------------------------------------|
| Physical Clay (A)  | 01/, 0/2, 0/4 | 4%                                     |
|                    | 0/8, 1/2, 1/4, 2/4 | 3%                                     |
|                    | 0/16, 0/32, 1/8, 4/8 | 2%                                     |
|                    | 0/63, 2/16, 4/16, 4/32 | 1%                                     |
|                    | 8/16, 8/32, 16/32, 32/63 | 0.5%                                   |
| Organic materials  | 0/4           | 0.5%                                   |
|                    | 4/63          | 0.1%                                   |
| Hardening-inhibiting materials | 2 | Concentration at which a concrete sample shows a decrease in strength above 15%. |
| Sulphur compounds  | 2 | 1%                                     |
|                    | 2 | 0.04% (reinforced concrete, cable concrete) |
| Chlorides          | 2 | 0.02% (pre-stressed concrete)           |
| alkalis            | 2 | No guidelines                          |

A further recommendation was developed by the International Union of Testing and Research Laboratories for Materials and Structures, according to which recycled aggregate should be divided into three classes [8]:

- RCAC I - aggregate obtained from brick rubble,
- RCAC II - aggregate obtained from concrete rubble,
- RCAC III - mixed recycled aggregate and natural aggregate.

This classification includes fractions above 4 mm, as it is assumed that the traditional requirements (European standards) for fine aggregates are satisfactory. The requirements for recycled aggregates (fractions above 4 mm) with regard to acceptable contaminants are presented in table 2 [8].

| Aggregate quality | RCAC [%] |
|-------------------|----------|
|                   | I | II | III |
| Maximum content of foreign materials | 5 | 1 | 1 |
| Maximum metal content | 1 | 1 | 1 |
| Maximum content of organic impurities | 1 | 0.5 | 0.5 |
| Maximum content of sulphates expressed as SO₃ | 1 | 1 | 1 |
Additional requirements are set for RCAC III aggregates:
- Minimum natural aggregate content: at least 80%,
- Maximum content of the type I aggregate: 10%.

According to RILEM guidelines, recycled aggregate must not contain any material or substance in a given concentration, at which the concrete strength drops below 75% of the strength of the sample with pure aggregate. In addition, any other requirements relating to the health and environmental aspects included in separate regulations must be met. The guidelines also set out a range of possible applications for aggregate in relation to the concrete class: for RCAC I the maximum concrete class is C16/20, for RCAC II the maximum class is C50/60 and for RCAC III there are no limits. It is to be noted that these recommendations are not binding until they are legally established in the country concerned.

2.3 Sources of impurities from recycled aggregates
In recycled aggregates, one can distinguish the following sources of pollution: initial concrete pollution, concrete pollution in the exploitation phase of the facility (chemical pollution), errors or negligence in the selective collection of waste on site, improper storage of waste, pollution acquired during transport.

These contaminants in recycled aggregate can occur as physical and chemical contaminants, their type and amount are significant for the re-use of the aggregate for concrete. Chemical impurities include mainly: alkaline compounds, chlorides, sulphate compounds. Physical impurities include: organic materials, clay materials and other building materials such as bituminous binders, glass, metal, plastics. Most of the impurities have a reducing effect on the concrete strength. For example, the addition of bituminous materials in the amount of 30% of recycled aggregate volume causes as much as a 30% decrease in concrete strength in relation to the pure recycled aggregate [9]. The standard EN-12620 [10] allows for up to 10% contamination of the aggregate with bituminous materials. However, most manufacturers set their own limit at the level of 5%. The source of bituminous binder in recycled aggregate are: asphalt, tar, roofing paper, pitch.

On the other hand, glass, due to its crystallographic structure, easily reacts with alkalis from e.g. cement. As a result of the reactivity in the presence of moisture, easily dissolvable hydrated silicates are formed, which increase in volume, which leads to the disintegration of the concrete structure and eventually to the destruction of the concrete [9]. One of the solutions limiting the possible occurrence of an alkaline reaction is the use of NA group cements and the reduction of the amount of cement in 1 m³ of concrete mix. Recommended quantity of glass should not exceed 1% of mass aggregate [10]. The source of glass in the secondary aggregate may be: glass windows, glass shapes, foam glass, glass wool.

Due to their low density, wood and plastics are easy to be selected. It is good practice to separate these contaminants by blowing out or washdrawing. A manual separation between the first and second degree of crushing is also used [9]. The maximum permissible content of wood and plastic in concrete is 0.1% by weight of aggregate. The sources of such materials are: boards, logs, floor strips, floor panels, plywood, chipboards, fibreboards, windows, doors, carpets, sanitary system elements. Another material easy to select is metal. Ferromagnetic metals are removed from the aggregate by magnetic strips, the rest of them are removed with the use of eddy currents. Metals have also been classified by the standard to the group of "other impurities", therefore their permissible amount should not exceed 0.1% [10].
An important type of impurity is gypsum, it requires restrictive removal. It results from the risk of sulphate expansion in concrete. The source of gypsum in recycled aggregate can be cardboard, dry screed, gypsum plaster, fire protection coatings for steel structures.

The assessment of chemical impurities occurring in recycled aggregate is important due to unknown original concrete parameters, as well as the content of corrosive factors resulting from exposure of the structure to unfavourable external factors. Alkaline compounds may originate from Portland cement and mineral additives to concrete, which induce ASR (alkali silica reaction) reactions in contact with resilient aggregate, i.e. aggregates containing reactive forms of silica, amorphous fuel, fibrous, tridymite, cristobalite or stressed quartz. Therefore, the maximum permissible concentration of alkali should be determined on a specific concrete mix on a case-by-case basis.

Sulphate compounds, in turn, can lead to sulphate corrosion. Sulphate corrosion is a process in which chemical reactions between the active components of concrete and sulphate ions can result in the formation of a highly expansive ettringite crystal. During crystallization, after filling the free space in the concrete pores, ettringite starts to exert pressure on the surrounding concrete pore walls. This pressure can cause micro-cracks in the hardened cement mortar and consequently reduce the elastic modules and weaken the structural element. Sulphated groundwater, acid rain, and so on can be the source of sulphate ions. The sulphate ions present in the surrounding environment migrate deep into the concrete due to diffusion and react with chemically active concrete components [11].

2.4 Environmental recycling of aggregates

In countries where natural aggregates resources are low, a number of advanced methods of concrete rubble recycling have been developed for a long time. Modern recycling methods are divided into methods based on abrasion of concrete aggregate slurry, where the obtained aggregate has similar properties to natural aggregate, and methods based on surface impregnation of recycled aggregates [12, 13].

Methods to remove adherent slurry from the natural aggregate are: Heating and rubbing method, Mechanical grinding method, Screw mill method and Gravity classification method. The most effective is the Heating and Rubbing Method [14]. All the above methods are connected both with high energy consumption and production of large amounts of dust, which have not been manageable so far and are not usable waste.

The method of aggregate sealing consists of immersing the recycled aggregate prepared in a traditional way in the cement slurry. Afterwards, the aggregate is coated and fractionated. As a result of these processes, the water demand of the aggregate is reduced and the workability of the mixture is improved [15].

All the methods presented herein lead to the complete decontamination of the aggregate, which for technical reasons seems to be beneficial. However, environmental aspects encourage research into the use of recycled aggregate without first subjecting it to energy consuming processes. A less cost-intensive alternative method of using recycled aggregate is the replacing method. It involves partial substitution of natural coarse or fine aggregate in the mixture with recycling aggregate. The replacing method requires selective demolition of buildings and detailed physico-mechanical characteristics of recycling aggregates as well as concrete mix and concrete with this aggregate [14]. This method corresponds to RILEM recommendations [8].

Investigations of the technical parameters of concrete carried out on recycled aggregate with impurities in terms of the replacing method, as an alternative to subjecting concrete rubble to expensive purification procedures, are presented in the following sections. It is worth pointing out that
in some countries the use of up to 20% of recycled aggregate does not require additional research and agreements. The research shows parameters using 50% recycled aggregate with impurities instead of natural aggregate.

3. Materials and Methods
The main purpose of the research was to obtain experimental results of selected physico-mechanical properties of concrete made on the basis of the natural aggregate as well as the recycled aggregate with impurities. It should be noted that in the past years, numerous works on the properties of secondary aggregates were carried out. However, in the majority of cases, the aggregate does not contain impurities [16–19].

In order to determine the typical composition of building rubble, a sample of aggregate from the demolition of a cubature object was taken. Physical impurities (foamed polystyrene, brick and glass) at the level of 5% by volume and other impurities in the amount less than 0.1% were visually identified in the collected sample. Next, the influence of the main impurities on the decrease of concrete compressive and tensile strength was investigated.

Six concrete mixtures with the same content of coarse aggregate and water-to-cement ratio were prepared for the tests. The first mixture contained only natural gravel aggregate (Figure 1/6), in the second mixture they were halfway replaced with recycled aggregate (Figure 1/5) and in the subsequent mixtures the recycled aggregate in 5% of its volume was successively replaced by impurities: glass, brick, foamed polystyrene and a combination of these impurities (Figure 1/1-1/4). Both impurities and recycled aggregate were prepared in 2/8mm fractions. The secondary aggregate was obtained as a result of concrete rubble crushing without impurities coming from concrete class C60/75 made on the basis of diabase. Compositions of concrete mixes per 1 m³ are presented in Table 3.

Mixtures were characterized by the same water-to-cement ratio at the level of 0.44. Due to the different content of natural aggregate and recycled aggregate, as well as the variety of impurities in individual concrete mixes, the batches were characterized by different water demand and thus by different consistency and workability. All mixtures were prepared in identical laboratory conditions, individual components were weighed with an accuracy of 1 g. The ingredients were combined in accordance with the practice of engineering and with the use of a mechanical mixer. In the study, 100 mm side cube specimens were used.

Figure 1. To the left: components of coarse aggregate in the tested concrete specimens. To the right: mix of aggregates and impurities
Tabela 3. Compositions of concrete mixes

| Components                        | Concrete mixtures |
|-----------------------------------|-------------------|
|                                   | I   | II   | III  | IV   | V   |
| Cement CEM I 32,5R                | 6.25|      |      |      |     |
| Natural gravel aggregate          | 14.3| 7.15 | 6.8  |      |     |
| Recycled aggregate                | -   | 7.15 | 6.8  |      |     |
| Impurities: glass (5% vol.)       | -   | 0.35 | -    | -    | -   |
| Impurities: brick (5% vol.)       | -   | -    | 0.35 | -    | -   |
| Impurities: foamed polystyrene    | -   | -    | -    | 0.024| -   |
| Impurities: Mix of glass, brick,  | -   | -    | -    | 0.257| -   |
| foamed polystyrene (5% vol.)      |     |      |      |      |     |
| Sand                              | 8.13|      |      |      |     |
| Water                             | 2.80|      |      |      |     |

All specimens were tested after 28 days of maturing in the same climatic conditions. In reference to the tested concretes, the standard compressive strength $f_{cm}$ on 6 specimens for each mixture, as well as the tensile strength by splitting $f_{ctm,sp}$ on 4 specimens for each mixture. The tests were performed using a hydraulic press and the surfaces of the samples were cleaned before the test.

4. Results and discussions

The results of the conducted tests are presented in Table 4, which contain average values of: bulk density, compressive strength and tensile strength as well as standard deviations of these results. The results are presented graphically in Figure 2.

Tabela 4. Summary of the results of tested material parameters

| Mixtures | Average volumetric density [kg/m³] | Average compressive strength [MPa] | Standard deviation [MPa] | Medium tensile strength [MPa] | Standard deviation [MPa] |
|----------|-----------------------------------|-----------------------------------|-------------------------|------------------------------|-------------------------|
| I        | 2315                              | 46.17                             | 1.03                    | 3.32                         | 0.12                    |
| II       | 2308                              | 43.13                             | 2.57                    | 3.68                         | 0.22                    |
| III      | 2311                              | 38.70                             | 1.25                    | 2.75                         | 0.28                    |
| IV       | 2303                              | 42.41                             | 1.57                    | 2.75                         | 0.35                    |
| V        | 2283                              | 38.65                             | 2.84                    | 2.71                         | 0.54                    |
| VI       | 2279                              | 41.28                             | 1.48                    | 2.59                         | 0.22                    |

On the basis of the conducted research, it was found that the average compressive strength decreased by 3 MPa, i.e. 6.5% of concrete made with 50% recycled aggregate (mix II), in comparison to concrete made only on natural aggregates (mix I). It should be noted that recycled aggregate had very high strength parameters (diabase aggregate). Mixtures I and II were treated as a reference and further research results are related to them. The highest strength reductions were noted in the case of contamination of recycled aggregate with glass and polystyrene (mixtures III and V), the decrease was 16.2% in relation to concrete made on natural aggregate (mixture I) and 10.3% in relation to concrete made with a 50% share of recycled aggregate (mixture II). The lowest reductions were observed in the case of brick aggregate contamination (mixture IV) - 8.2% and 1.7% in relation to the mixture I and mixture II, respectively. Mixture VI containing mixed impurities was characterized by a drop in the level of 10.6% in relation to the mixture I and 4.3% in relation to mixture II.
With regard to tensile strength, an increase in the tensile strength of mixture II, which included recycled aggregate, was noted. This may result from the mechanism of destruction of high-performance concretes (such as the used concrete from which recycled aggregate originated). Unlike ordinary concretes, the destruction surface in HPC is both through the matrix and through aggregate particles [20], which is visible at the cross section of a tested concrete specimen (figure 3). On the other hand, a significant decrease in tensile strength has been recorded in the case of mixtures with impurities, which amounts to about 20% and does not show the dependence on the type of contamination.

**Figure 2.** The average compressive strength of reference and impurities samples

**Figure 3.** One of the specimens tested in a tensile splitting process

5. Conclusions

The results of the research indicate the significant impact on the technical parameters of concrete of the type of impurities present in aggregates from the recycling of construction rubble. The most frequent contaminant of concrete rubble, which can be considered as bricks, does not cause significant decreases in the compressive strength. The worst parameters were visible in the concrete, in which 5% of recycled aggregate was replaced by glass and polystyrene impurities. Glass is also an unfavourable pollutant from the point of view of the concrete chemistry, because it reacts strongly with alkalis, resulting in expansive salts. Hence, in the case of the presence of glass in aggregates, the appropriate type of cement is to be used.
The mixture prepared on recycled aggregate containing 5% by volume of the mixed impurities (brick, glass, foamed polystyrene) had slightly worse strength parameters than the mix of the recycled aggregate without impurities. However, the registered strength reduction does not correspond to the expected results and is not determined by the highest drop that has been noted, nor is it a superposition of these drops.

The results of the tensile strength tests do not allow drawing unambiguous conclusions. It is most likely due to the type of recycled aggregate used (high-performance concrete). However, the tensile strength of concrete will not be a key technical parameter due to the performance of the concrete elements that are designed as the compressed elements.

It seems reasonable to use the technology replacing up to 50%, supplementing the natural aggregate with the recycled aggregate. Aggregate purification technology should be adapted to the requirements of natural aggregates. However, the research has shown that it is not necessary to purify the aggregate completely because the energy consumption of these processes is not considered to be worth the benefits that can be obtained. Aggregate washdown process may be advisable. In this process, there is an elimination of dust fraction present in debris and separation of light impurities such as foamed polystyrene.

References
[1] M. Behera, S. K. Bhattacharyya, A. K. Minocha, R. Deoliya, and S. Maiti, "Recycled aggregate from C&D waste & its use in concrete - A breakthrough towards sustainability in construction sector: A review", Constr. Build. Mater., vol. 68, pp. 501–516, 2014.
[2] M. Etxeberria, E. Vázquez, A. Mari, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", Cem. Concr. Res., vol. 37, no. 5, pp. 735–742, 2007.
[3] Y. Zhang, W. Luo, J. Wang, Y. Wang, Y. Xu, and J. Xiao, "A review of life cycle assessment of recycled aggregate concrete", Constr. Build. Mater., vol. 209, pp. 115–125, 2019.
[4] D. Wałach, P. Dybel, J. Sagan, and M. Gicala, "Environmental performance of ordinary and new generation concrete structures — a comparative analysis", Environ. Sci. Pollut. Res., no. 26, pp. 3980–3990, 2019.
[5] A. Sobotka and J. Czaja, "Analysis of the Factors Stimulating and Conditioning Application of Reverse Logistics in Construction", Procedia Eng., vol. 122, no. Supplement C, pp. 11–18, 2015.
[6] A. Sobotka, J. Sagan, M. Baranowska, and E. Mazur, "Management of reverse logistics supply chains in construction projects", Procedia Eng., vol. 208, pp. 151–159, 2017.
[7] M. Martin-Morales, M. Zamorano, I. Valverde-Palacios, G. M. Cuenca-Moyano, and Z. Sánchez-Roldán, "Quality control of recycled aggregates (RAs) from construction and demolition waste (CDW)", Handb. Recycl. Concr. Demolition Waste, pp. 270–303, 2013.
[8] RILEM RECOMMENDATION, "Specifications for concrete with recycled aggregates", Mater. Struct., vol. 27, no. 9, pp. 557–559, 1994.
[9] R. V. Silva, J. De Brito, and R. K. Dhir, "Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production", Constr. Build. Mater., vol. 65, pp. 201–217, 2014.
[10] EN 12620 - Aggregates for Concrete. 2013.
[11] X. Qiao and J. Chen, "Correlation of propagation rate of corrosive crack in concrete under sulfate attack and growth rate of delayed ettringite", Eng. Fract. Mech., vol. 209, no. February, pp. 333–343, 2019.
[12] C. Shi, Y. Li, J. Zhang, W. Li, L. Chong, and Z. Xie, "Performance enhancement of recycled concrete aggregate - A review", J. Clean. Prod., vol. 112, pp. 466–472, 2016.
[13] A. Akbarnezhad and K. C. G. Ong, "Separation processes to improve the quality of recycled
concrete aggregates (RCA)", in Handbook of Recycled Concrete and Demolition Waste, 2013, pp. 246–269.

[14] B. Zając and I. Gołębiowska, "Nowoczesne metody recyklingu betonu", Inżynieria I Apar. Chem., no. 5, pp. 136–137, 2010.

[15] J. Mądrowski, "Możliwości poprawy cech betonów na kruszywach recyklingowych", Acta Sci. Pol., vol. 6, no. 1, pp. 3–10, 2007.

[16] D. Wałach, "Możliwości powtórnego wykorzystania kruszywa pochodzącego z recyklingu betonów wysokowartościowych", Logistyka, no. 6, pp. 14855–14864, 2014.

[17] M. Malešev, V. Radonjanin, and S. Marinković, "Recycled concrete as aggregate for structural concrete production", Sustainability, vol. 2, no. 5, pp. 1204–1225, 2010.

[18] K. P. Verian, W. Ashraf, and Y. Cao, "Properties of recycled concrete aggregate and their influence in new concrete production", Resour. Conserv. Recycl., vol. 133, no. February, pp. 30–49, 2018.

[19] K. Helal, H. Istaitiyeh, A. Zaher, S. Yehia, and A. Abusharkh, "Strength and Durability Evaluation of Recycled Aggregate Concrete", Int. J. Concr. Struct. Mater., vol. 9, no. 2, pp. 219–239, 2015.

[20] D. Wałach, "Impact of the Research Conditions on the Accuracy of the Designation of High Performance Concrete Strength Parameters", Arch. Civ. Eng., vol. 62, no. 4, pp. 139–151, 2016.