Assessment of recycled concrete aggregate properties required for structural concretes

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Abstract. Assessment of recycled aggregate concrete (RAC) properties by laboratory tests is still required due to lack of precise guidelines and with taking into account slightly different behaviour of such concretes in comparison with natural aggregate concretes (NAC). It is especially important when recycled concrete aggregates are used for the structural elements. In this paper, the following rules for the whole concrete recycling cycle were defined: (1) rules for examination of original concretes selected for recycling and (2) rules for aggregate preparation and their fractionize as well as design rules for recycled aggregate concrete mixtures (including required tests of recycled aggregates and concrete properties). Requirements towards recycled aggregate concrete formulated in this paper are based on the long term experience and research works on the RAC which were held by A. Ajdukiewicz and A. Kliszczewicz in the Department of Structural Engineering of the Silesian University of Technology, practically since 1995.

1 Introduction

Research on the use of recycled concrete aggregates for the production of new structural elements has been carried out worldwide for a long time. Many tests confirm safe use of them in the structures.
Nevertheless, until recently, the lack of appropriate building standard requirements was a barrier in use of such aggregates. Standards dealing with concrete as a material, as well as design standards of concrete structures, have, until recently, not involved recycled concrete aggregates.

Thankfully, in recent years, building standards have extended the range of aggregates that can be used, among all, also involving the concrete recycled aggregates. Thus, it is now possible to deal with them in production of new concretes.

Based on the experience from previous research and with reference to current standards, in this paper, Authors described the main steps for assessment of recycled aggregate properties required for structural concretes, adding also some basic guidelines for design of recycled aggregate concrete mixtures.

2 Aggregates from recycled concrete debris in terms of current standards

Attempts to create a model of rational concrete recycling took place in various countries as well as in the international organizations. In 2004, the *fib* (International Federation for Structural Concrete) Task Group 3.3 published the *fib* Bulletin No. 28 "Environmental design" [1] - a state-of-art report of previous achievements also in the field of concrete recycling in Europe and Japan. Works and documents of various research teams were taken into account, which were the result of comprehensive activities and attempts to search for optimal solutions from among the available so-called BAT (Best Available Technology) system.

Three areas of application of recycled concrete aggregates were distinguished, taking into account the quality of the original material - from the worst to the best. These are the following areas:
(1) low quality aggregates used as back-fill or road sub-base materials (e.g. paving stone, earthen floor stone),
(2) materials for non-structural concrete, or used as an additive to natural aggregates to a limited extent (e.g. 20-40%), giving satisfactory results with relatively low strength requirements (e.g. foundations, massive walls, levelling concrete, subslab concrete etc.),
(3) materials for structural concretes, constituting full-value aggregate - course and fine, or only coarse aggregate.

Currently, the basic concrete standard PN-EN 206+A1:2016-12 [2] applies to a wide group of both ready-mixed concretes as well as concretes produced in the precast plants. It is therefore a basic document concerning among all the possibility of using recycled concrete aggregates.

In particular, the Standard [2] introduces application rules for concrete with recycled aggregates (i.e. aggregates resulting from the processing of inorganic material previously used in construction).

Recommendations for use of coarse recycled aggregates with d > 4 mm are given in Annex E. Standard [2] divides recycled aggregate into two types: A (concrete aggregate) and B (aggregate from masonry). Limits for the replacement of natural normal-weight

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coarse aggregates by coarse recycled aggregates in relation to exposure classes are provided and are shown in Table 1.

Table 1. Replacement limits of coarse aggregates (% by mass) according to PN-EN 206+A1:2016-12 [2], Table E.2.

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A	50%	30%	30%	0%
Type B [b]	50%	20%	0%	0%

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%.
[b] Type B recycled aggregates should be used in concrete with compressive strength classes > C30/37.

All changes to legal acts concerning aggregates in the last years result from the European Union policy on effective waste disposal. One from the important activities of the European Commission was the Mandate M/125 [3] for CEN (European Committee for Standardization) to develop harmonized standards for aggregates. The first effect of these activities was the introduction of a new division of aggregates (natural, artificial and recycled) in the definition of aggregate as a granular material used in construction.

In the years 2010 ÷ 2011, the CEN/TC 154 Committee, as part of the implemented amendment, introduced a detailed division of aggregates. It also introduced the normative Annex A (Sources for raw materials) which considered all the raw materials that can be used to produce aggregates and described sources of their origin.

This annex is present in the PN-EN 12620:2010 [4].

The aggregates in this standard are divided into three groups:
(1) Natural aggregates from mineral sources which has been subjected to nothing more than mechanical processing (crushing, grading or washing) – e.g. sand, gravel, crushed stone, lime rock,
(2) Manufactured aggregates of mineral origin resulting from an industrial process involving thermal or other modification – e.g. blast-furnace slags and cinders, fly ash, etc.,
(3) Recycled aggregates resulting from the processing of inorganic or mineral material previously used in construction.

Recycled aggregate has specific properties and its suitability for concrete production is not defined in exactly the same way as natural aggregate. The main standard for aggregates for concrete PN-EN 12620+A1:2010 [4] includes for the first time aggregates from recycling. The same refers to the related standards: PN-EN 1744-1+A1:2013-05 [5], PN-EN 1744-5:2008 [6], PN-EN 1744-6:2008 [7], PN-EN 933-11:2009+AC:2010 [8] and PN-EN 1367-4:2010 [9].

Recycled aggregate must be qualitatively determined by its composition. A simple method for the examination of coarse recycled aggregates is specified in the Standard [8], for the purpose of identifying and estimating the relative proportions of constituent materials.

According to the Standard [8], among the constituents of coarse recycled aggregates the following are defined:
• concrete, concrete products, mortar and concrete masonry units (*Rc*),
• unbound aggregate, natural stone and hydraulically bound aggregate (*Ru*),
• clay masonry units (i.e. bricks and tiles) and calcium silicate masonry units, aerated non-floating concrete (*Rb*),
• bituminous materials (*Ra*),
• floating material (*FL*),
• glass (*Rg*), and:
• a group of all other materials, including cohesive compounds (i.e. clay and soil), metals (ferrous and non-ferrous), non-floating wood, plastic, rubber and gypsum plaster (*X*).

This qualification is the main determinant of aggregate quality and its usefulness for a particular product and is the most important parameter differentiating its quality.

In addition, supplementary tests of recycled aggregates are required to specify the following properties: chloride content [6], sulfates content [5] and resistance to ambient conditions [9].

A very important feature that differentiates natural and recycled aggregates is the variability of parameters between individual batches of recycled aggregates. The Standard [4] in the appendix H also determines the recommended frequency of production control. Relatively more frequent controls are required in relation to natural aggregates, as well as a larger number of different tests shall be performed.

The annex ZA in the Standard [4] establishes the conditions for the CE marking of natural, manufactured or recycled aggregates.

Recycled aggregate may be now classified and identified by CE marking symbol with the purpose of legal use in construction. It means, that the producer of recycled aggregates is obliged to carry out the required tests and properly identify the packing with the appropriate CE marking symbol.

3 General rules for assessing the quality of demolished concrete for the production of recycled aggregates

Systemic operation in obtaining the appropriate quality of recycled materials requires selective demolition of building objects with division into individual batches of materials, and often also preliminary assessment of material properties on site, before its demolition. This procedure facilitates the processing of recycled materials into various material groups. Therefore, demolition of facilities and processing of recycled materials requires incorporating specialized firms.

To reach the appropriate quality of recycled aggregate from waste and contaminated concrete debris for the production of new structural concretes, the appropriate equipment and processing technology is required.

To obtain recycled aggregates requires coordinated actions, such as:
• selective demolition of an object with division into material groups; initial breaking of large elements and segregation of materials; transport of debris to the processing plant, or - in the case of a large object - locating the processing line directly in the vicinity of the demolished object,
• initial crushing and separation of reinforcing steel and other contaminates,
• essential crushing, fractionation of aggregates,
• possible refining of the aggregate,
• packing of aggregates,
• aggregate distribution.

Determination of the quality of demolished concrete selected for recycling and further use in structural concretes requires conducting the following steps:
• macroscopic evaluation,
• strength tests,
• chemical research.

It is advisable that preliminary identification tests should be carried out on site and before demolition.

3.1 Macroscopic evaluation

For concrete elements intended for crushing, the concrete condition should be assessed macroscopically directly on site or at the storage yard. A lot of valuable information is provided by a thorough visual inspection of the concrete surface with purpose to identify any damages and surface contamination. It would be favorable to recognize the service life conditions, the age of concrete and the ambient conditions. These data would determine the scope of further research.

3.2 Strength tests

An important factor in the assessment of the quality of recycled concrete aggregates in particular in case of structural elements is the assessment of demolished concrete strength. It can be done directly on site by non-destructive methods, e.g. using the sclerometer - rebound Schmidt hammer, or in the laboratory by means of specimens testing (core tests). This stage of research is very important as it will determine the possible scope of application of debris. Testing core samples, if possible, enable more accurate identification of concrete properties (including its mechanical properties).

3.3 Chemical research

In order to assess the quality of concrete on site, in the element dedicated to crushing, the following tests are necessary:
• determination of the alkalinity of concrete (pH),
• determination of sulphate content (SO_4^{2-}) in the concrete binder,
• determination of the chloride content (Cl^-) in the concrete binder.

3.3.1. Chemical research on site

In order to evaluate the quality of concrete intended for crushing, it is necessary to examine the alkalinity of concrete (pH - factor) in order to determine the degree of carbonation of concrete. The degree of carbonation of concrete does not influence the quality of the aggregate obtained after crushing, but it can indicate the corrosive impact on a particular element or structure during the exploitation period. A reduced pH (< 6) may indicate acidic corrosion, which is often the case in reinforced concrete chimney walls. On the other hand, the very high alkalinity of recycled aggregates ($pH > 12.5$), may cause that the recycled aggregate concrete would reach pH value about 13. Concrete with such a strongly alkaline reaction should not be used in contact with galvanized steel sheets, e.g. in the culverts structures.

The pH-factor of concrete can be roughly determined directly on site by means of indicator papers (e.g. *Whatman* or *Duotest*), with the pH range $6 \div 12$, and with an accuracy of 0.5.

The alkalinity test should be carried out on the surface of the concrete and at 10 mm and 20 mm thick near surface concrete layers.

After hammering, the concrete surface should be moistened with distilled water and the indicator paper should be pressed down.

The pH value of the concrete is determined by comparing the indicator paper color with the standardized colors.

Additionally, the following color indicators are useful for testing the pH of the concrete:
• phenolphthalein (2% alcoholic solution) changes color from colorless to raspberry at $pH \cong 8$,
• thymol blue or thymolsulphonephthalein (alkaline solution) changes colors from yellow to yellow-blue at $pH \cong 9$ and intensely blue at $pH \cong 12$.

The phenolphthalein index is also very useful for determining the thickness of a completely carbonated layer of concrete in the location of boreholes or in the fracture surface of concrete and reinforced concrete elements.

Sound concrete structure, even after several decades of service life, should display a clearly alkaline reaction ($pH > 10$) at distances of 10mm and 20mm from the surface (see Fig. 1).

Fig. 1. Concrete sample tested after 50 years of service life.

If the reaction of concrete at a depth above 20 mm is inert ($7 \geq pH < 8$) or slightly acidic ($pH < 7$), a concrete sample should be taken for chemical testing in the laboratory.

Also in case of structures subjected to aggressive media, it is necessary to perform laboratory chemical tests of concrete.

3.3.2. Laboratory chemical tests of concrete

In particular, the following chemical laboratory tests of the concrete samples shall be conducted: evaluation of the reaction of concrete and determination of the content of sulphates (SO_4^{2-}) and chlorides (Cl^-) in the concrete binder.

The pH value and chloride content are determined in water extracts obtained after boiling of the crushed concrete samples in water. The content of chlorides in the binder of concrete samples should be determined in accordance with PN-EN 196-2:2013-11 [10].

In solutions, after digestion with dilute hydrochloric acid, the sulphate ion content is determined by gravimetric method. In order to determine the content of chlorides and sulphates in the binder, it is necessary to determine the content of aggregate and cement in hardened concrete. The amounts of aggregate and cement in concrete should be determined in accordance with The Polish Building Research Institute instruction No. 277 (1986) - for determining the composition of hardened concrete.

The content of sulphates (as SO_3) in produced cements, according to PN-EN 197-1 [11], cannot exceed 3.5% for CEM I and CEM II and 4.0% for CEM III and CEM IV. Therefore, the sulphate content in recycled concrete aggregates exceeding these values, may cause a risk of sulphate corrosion for the new concretes.

Due to the corrosion hazard for reinforcing steel, in accordance with the PN-EN 206 [2], chloride content in the binder cannot exceed 0.4% in ordinary reinforced concrete elements (and 0.2% in prestressed reinforced concrete elements). Recycled concrete aggregate used for the production of reinforced concrete elements should not contain more than 0.2% of chlorides in the binder. According to standard [11], all cements may contain up to 0.1% of chlorides. The use of an acceptable limit value of 0.4% chlorides for recycled aggregates may result in exceeding the chloride content threshold in new, recycled aggregate concrete.

3.4 Criteria for assessing the quality of concrete

Exploited concrete can be considered useful for crushing and re-use as aggregate for structural concrete if satisfies the following requirements:
• has adequate strength (at least C12/15) and a sound structure,
• has an alkaline reaction ($pH > 10$) at a depth of 10mm ÷ 20mm from the surface,
• the content of chlorides (Cl^-) in relation to the mass of the binder does not exceed 0.4%,
• the content of sulphate ions [SO_4^{2-}] does not exceed 3% of the mass of the binder.

4 Guidelines for design and preparation of concrete mixtures

A procedure similar to the traditional one is proposed in the selection of compositions of concrete mixtures with recycled concrete aggregates. However, it is advisable to recognize the basic differences in the properties of recycled aggregates in relation to natural aggregates. They highly depend on the properties of exploited concrete, such as: strength, immediate and long-term strains, absorption, thaw and freeze resistance, water permeability.

4.1 Properties of recycled aggregates

The properties of recycled aggregates differ from new aggregates and depend to a large extent on the original concrete properties from which they were obtained. The most important differences are:
• higher porosity, and thus greater absorption (the larger for the low strength and more porous original concrete),
• greater roughness,
• high content of fines (the greater for low strength original concrete), affecting a strong increase in water demand,
• thaw and freeze resistance of the aggregate with regard to the porosity of the aggregate (lower for low strength and porous original concretes),
• crushing strength (to a large extent dependent on the strength of the original concrete),
• lower bulk density - resulting from the density of the original concrete.

4.2 The scope of recycled concrete aggregate tests

The minimum scope of necessary tests of recycled concrete aggregates, enabling design of new concrete mixture, does not differ from that required for the design of traditional concrete mixtures, and therefore it is necessary to:

• determine the grain composition (sieve analysis) for individual fractions of aggregates,
• determine the density of aggregates,
• perform humidity test - to correct design recipes.

For large batches of aggregates, it is advisable to carry out full tests of aggregates, which periodically are performed by the aggregate plants. The indication for testing of contaminates should result from the assessment of the degree of hazard and the type of contaminates, after analyzing the service life of the element, method of demolition, as well as location and storage time period of concrete debris.

The most difficult task would be to determine the water demand indexes (probably different for different batches of aggregates), therefore it is proposed to determine the amount of water required in the mixture by tests.

In the production of aggregates on an industrial scale, it would be advisable to develop the classification of aggregates to specify their properties, which would greatly facilitate the selection of aggregate and provide appropriate data for design.

4.3 Evaluation of the refinement possibilities of aggregates

A high content of fines in recycled aggregates causes a significant increase in water demand.

However, refinement of the 0÷2 mm fine aggregates is not recommended by increasing the amount of fines, because they have binding properties and they are difficult to remove from the large aggregate mass. In addition, they cannot be treated as a cement substitute, as their binding properties are weak - they also depend on the age of the crushed concrete, the storage period of recycled aggregate, and also on ambient conditions. If the recycled aggregate of the fine 0÷2 mm fraction is used for the new concrete, it should be protected against the early reaction with water.

Recycled aggregate is aging faster than natural aggregate, and therefore it should be used as soon as possible after crushing. It should not be subjected to long-term ambient exposure. If a longer storage time period is required, the dried aggregate should be protected with sealed packaging and stored under requirements applying for binding materials.

The recommended method of getting rid of a large part of the fines is traditional screening with suction.

4.4 Preparations and technological treatment of recycled aggregate concrete mixtures

Universal method of design of recycled aggregate concrete mixture cannot be specified due to the difficulty in assessing the basic property of these aggregates - water demand - largely dependent on the properties of the original concrete. Determining of the water demand would be labor consuming. Use of water-to-binder ratio, very helpful in traditional design, is also questionable, due to considerable and very diversified water demand of the recycled aggregate.

A more porous recycled aggregate (which varies - depending on the porosity of the original concrete) absorbs a large part of the mixing water. This requires, during the mixture, a specific time period for the aggregate to fully saturate. If this condition is not met, the consistency of the mixture must be reckoned during concreting - to the extent that the concrete cannot be cast properly. Additional water needed to saturate the recycled aggregate is therefore necessary to allow concreting. After full saturation, this water remains inside the aggregate and does not affect the liquidity of the mixture. It is difficult, however, to assess to what extent it affects the properties of hardened cement paste. It seems that this unbound water should have a beneficial effect on cement binding, because there is no excessive water drawing by the aggregate, and the concrete is additionally cured from the inside. It can also have a beneficial effect on the characteristics of recycled aggregate, which is to some extent active, especially when it comes from relatively young concrete.

Therefore, it is proposed to use traditional analytical methods for designing the basic composition of the concrete mixture, preceded by the definition of an aggregate skeleton, taking into account the actual density of recycled aggregates and the water demand indexes used for natural aggregates. The necessary additional water should then be determined experimentally, by adding water to obtain the expected consistency, bearing in mind that the recycled aggregate must be previously saturated with water.

The following procedure is proposed for the preparation of a concrete mixture with recycled aggregate:
• weighing the appropriate amount of dry aggregate, and - directly in the concrete mixer - adding a part of the mixing water and mixing,
• waiting for the aggregate to soak (minimum 1 hour),
• adding a complementary natural aggregate with another portion of water and mixing,
• adding cement and ashes (if required) with the last portion of water,
• after another mixing, adding a superplasticizer (if provided).

With this procedure, concrete mixtures with significantly better workability are obtained than with conventional simultaneous mixing and sufficient saturation of the recycled aggregate is ensured.

It is also advisable to check the mixture composition and the properties of concretes in the trials. In case of significant differences, the project should be adjusted.

5 Predicting recycled aggregate concrete properties

Based on the results of research conducted in a number of countries worldwide, comparing recycled aggregate concretes (RAC) with analogous natural aggregate concretes (NAC), the following features of RAC were recognized:
• lower compressive strength (approximately in range of 10 ÷ 30%),

• lower tensile strength (approximately of 10%),
• lower modulus of elasticity (approximately in range of 10 ÷ 40%),
• greater shrinkage (approximately of 55%),

In particular, the modulus of elasticity of recycled aggregate concrete differs quite significantly – which is by the way also observed in natural aggregate concrete depending on the type of aggregate (quartzite, granite, basalt etc.). This problem is not clearly solved yet in Eurocode 2. On the other hand, the value of the elastic modulus will not be significant in all structural elements and therefore it does not always affect use.

On the other hand, no significant differences were found - in relation to concretes on natural aggregates - in terms of thaw and freeze resistance, bond properties and workability.

Based on the Authors experience [12], [13] it appears that for the recycled aggregate concretes, in which the fine aggregate was replaced with natural sand - in comparison with natural concrete aggregates, the differences in properties are clearly lower in relation to natural aggregate concretes.

On the basis of the analysis of the results of external and Authors research, it is currently not possible to present unambiguous recommendations, allowing to determine the expected properties of concretes even with known basic features of recycled aggregates. Only an approximate estimation is possible.

In assessing level of decrease in individual recycled aggregate concrete properties, the following factors should be taken into account:
• compressive strength of the original concrete,
• age of the original concrete,
• amount of recycled aggregate in the total weight of aggregate.

6 Summary

Majority of worldwide laboratory tests of structural elements made from the recycled aggregate concrete (RAC) give promising results, especially when high quality recycled aggregate is used and the replacement ratio of natural aggregates is limited. Therefore, proper assessment of quality of recycled concrete aggregate properties on site and in the laboratory is required. It is particularly important for structural concretes – production system for high quality aggregate must be provided. In this paper, basic guidelines were formulated for evaluation of the quality of demolished concrete for the production of recycled concrete aggregates by means of macroscopic evaluation, strength tests and chemical research. Subsequent design procedures of recycled aggregate concrete mixtures were defined, in particular with focus on technological treatment of recycled aggregate. In addition, the overview of the current situation in the Polish building law regulations about the use of recycled aggregate concrete for structural elements was presented.

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