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REVIEW ON RADIOACTIVE CONCRETE RECYCLING METHODS

R. DEJU[1], M. DRAGUSIN[1], I. ROBU[2], C. MAZILU[2], C.TUCA[1]

[1] "Horia Hulubei" National Institute for Physics and Nuclear Engineering, IFIN-HH Bucharest
P.O. Box MG-6, Magurele, Romania
[2] Technical University of Civil Engineering Bucharest
Lacul Tei Bvd., no. 122 – 124 RO 020396, sector 2 Bucharest, Romania
Corresponding author: dejuradu@yahoo.com

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Abstract. The article presents the way in which recycled concrete aggregates' properties influence the features of the new concrete. There are discussed classic and innovative methods for radioactive concrete recycling, having as main purpose the increase of the radioactive waste volume. The authors perform an evaluation of the national level technique status, and also a comparative analysis between radioactive concrete recycling techniques.

Key words: recycled concrete aggregates, recycled aggregate concrete, reuse and recycling of radioactive waste, classic and innovative methods, radioactive concrete recycling methods.

1. INTRODUCTION

At the end of 2011 worldwide there were 124 power reactors shut down, from which: 16 fully decommissioned, 50 power reactors in a decommissioning process, 49 reactors in "safe enclosure mode", 3 reactors "entombed", for other 6 reactors it wasn't yet have specified the decommissioning strategy [1].

A large part of the construction materials resulted from decommissioning activities are inactive and can be free released and disposed, using conventional methods according with the legal requirements.

Also, it is well known that during operation, maintenance or repairing these plants, a part of the concrete structures involved can become radioactive (contaminated/activated). Thus, decommissioning of the nuclear plants produces large quantities of radioactive waste, mostly being represented by concrete waste.

After the decommissioning of:

– a light water cooled nuclear-electrical power plant (900÷ 1300 MWe), results about 600 tons of radioactive concrete waste [2];

– a gas cooled nuclear-electrical power plant (Tokai-1, 166 MWe), results about 10,000 tons of radioactive concrete waste [3];

– a nuclear research reactor (KRR-2, 10 MW power), results about 260 tons of radioactive concrete waste out of a total amount of 2,000 tons of concrete waste [4].

Now, in Europe the amount of recycled radioactive concrete waste is between 1200÷2000 tons/year especially resulted from Great Britain facilities, following that after 2030 to increase at about 7,000 tons/year. The final disposal of those materials involves major problems because the facilities and the final disposal technologies are limited and expensive. Thus, the amount of waste arises from operating and decommissioning activities represented an impediment to place nuclear power plants in some parts of the world. Waste recycling and volume reduction are essential in decreasing the costs of decommissioning nuclear facilities.

The main elements of waste management strategy can be divided in four fields: reducing the source, preventing the spreading of contamination, recycling-reusing and waste management optimization. The first step of any waste management strategy is keeping to a minimum the generation of radioactive waste, goal achieved by a proper radiological characterization and segregation of waste.

Radiological characterization is important to obtain data regarding physical, chemical and radiological characteristics of these materials, in order to segregate, process and/or final dispose them. Segregation promotes maximizing the free release, reusing or recycling materials, and allows volume reduction of radioactive waste that does not fulfill criteria for free release, recycling or reusing.

The requirements regarding nuclear and radiological safety, environmental protection, transport, treating, conditioning, interim storage and final release for radioactive materials have become more restrictive in the last years. Public acceptance for nuclear field induces constraints for the processes of regulation, control, authorization, safety and physical protection.

During 1999÷2005 in EC there were made studies focused on research-development having as main purpose to increase the recycling amount of radioactive material in a safely, economic and environmental friendly manner. Still, there were not published specific technical data over this subject, but only information regarding the experience in this field of countries like Belgium, Spain and Great Britain – B.Y. Min *et al.* [5], suggesting that the lack of information in this field is caused by the fact that significant volumes of recycled concrete will not arise sooner than 2025.

2. RECYCLED CONCRETE AGGREGATES AND THEIR PROPERTIES

The developed technologies are showing that recycled concrete radioactive waste is used as:

– aggregates (rubble, coarse powder and fine powder) resulted out of a technological process that includes crushing, grinding, sorting and dimensional cutting;

– the sludge resulted during concrete blocks cutting operations which are conditioned by dehydration.

P. K. Metha and P. J. M. Monterio [6] have shown that aggregates (aprox.70% of the volume of the Portland cement concrete) are the main concrete component which determines the relation between its strength and density. The concrete obtained with recycled concrete aggregates (RCA) is called recycled aggregates concrete (RAC). I. B. Topçu and N. Fuat [7] have shown that basic properties of RCA, such as shape, texture, density, volume water absorption, humidity content, diffusion, strength, harming substances, freeze-thaw strength, must be determined before using them in the composition of the new concrete, in order to obtain fresh concrete with adequate workability, stability and cohesion, as well as for avoiding large variations in the properties of hardened concrete. M. C. Limbachiya *et al.* [8] have shown that RCA can be used for a certain application only if they fulfill the requirements established in applicable specifications. RCA differ from natural aggregates (NA) by the fact that they are composed by two materials: natural aggregates and an adhered mortar layer which remains after crushing operation. S. R. Yadav and S. R. Pathak [9] have observed that more than 50% of the recycled aggregates have the adhered mortar layer, giving them a larger porosity, thus a lower quality. M. Tsujino *et al.* [10] have determined the constituents of the larger grained aggregates, and they established that about 30% wt. of medium quality aggregates, and more than 50% wt. of low quality aggregates is represented by mortar. M. Sanchez de Juan and P. A. Gutierrez [11] have observed that the main factor of influence in mortar content is the size of the aggregates. The content of adhered mortar is larger in the fine fraction than in the coarse fraction. These properties have a negative effect over the quality of recycled concrete, mostly affecting elasticity, shrinkage, creep, durability, and less strength. Increasing the number of crushing phases will determine decreasing of the adhered mortar quantity as well as increasing the quality of the resulted aggregates. On the other hand, increasing the number of crushing phases will increase the production costs, thus there must be established a balance between the number of crushing phases and the quality of the aggregates obtained. J. Yang *et al.* [12] have shown that the main difference between RCA and NA is the water absorption rate. D. Jevtić *et al.* [13] have observed that RCA water absorption capacity is much larger than NA, depending on the RCA quantity and also on the porosity of the newly obtained concrete matrix, from which RCA were obtained. It is increasing supplementary with quality and thickness of the adhered mortar layer around the original grains and decreasing size of the grains used in the original concrete (a bigger specific surface area needs a larger amount of adhered mortar). The fine NA substitution with RCA increase capillarity water absorption, due to the more porous structure of both RCA and obtained RAC. M. C. Limbachiya *et al.* [8] have shown that, due to the adhered mortar (adhered cement composition) in RCA, the density of those materials is about 3÷10% lower and water absorption is about 3÷5 times bigger than the one corresponding to the NA. When water absorption is bigger, this will determine a decrease of workability in the fresh concrete. T. Ishikura *et al.* [14] showed that these features RCA and RAC deficiencies can be corrected by choosing the correct ratios of mixed constituents and additives.

3. STATUS OF CONVENTIONAL AND INNOVATIVE TECHNOLOGIES

3.1. STATUS OF TECHNOLOGIES AT INTERNATIONAL LEVEL

3.1.1. Application fields

The application field for reusing radioactive concrete in the nuclear industry includes:

a) manufacturing of radiological protection shields;
b) manufacturing of prefabricated items:
   – containers, cells and vaults for final disposal of waste in surface disposal facilities;
   – beams and segments for construction of depth geological disposal facilities;
c) preparing of material for infilling, completing or encapsulating waste containers used in near surface disposal facilities;
d) preparing mortar for immobilization of solid low level wastes;
e) preparing mortar for waterproofing;
f) building of new facilities.

3.1.2. Manufacturing of radiological protection shields

Manufacturing of radiological protection shields is a necessity and it is widespread in nuclear technology. The shielding are manufactured out of metal or concrete, and are designed to ensure a relative wide section for neutrons absorbing, in order to minimize radiation transmission from a structure bounded space, towards the environment, or for reducing the energy of such radiation to an non harming value. Conventionally, the concrete shielding is made out of NA.

M. Sappok [15, 16], R. S. Kingsley [17] and B. A. Roy *et al.* [18, 19] have proposed using of radioactive concrete aggregates, instead of natural aggregates, for manufacturing radiological shielding, minimizing the volume of radioactive waste. The method developed by above mentioned authors demonstrates that radioactive concrete aggregates can be easily incorporated in new shielding structures, with the condition that the radioactive waste must have, before using it in the concrete manufacturing process, a specific activity equivalent of Co 60 ≤ 100 Bq/g.

It is estimated that [20] are necessary 1,200 tons of concrete blocks for building a shielded enclosure. Natural aggregates can be totally replaced by recycled radioactive fine aggregates/rubble, so result a necessary of recycled radioactive concrete of about 1,000 tons/enclosure.

3.1.3. Manufacturing of prefabricated items

B. A. Roy *et al.* [18, 19] have proposed manufacturing of containers for processing, isolation, final disposal or for interim storage of radioactive waste or dangerous materials made of RAC, having various dimensions, shapes and capacities. In a cylinder shaped container are placed steel drums containing radioactive or dangerous waste in liquid, solid or compacted shape. The container's walls do not come directly in contact with the waste. The container's walls and cover have RCA in their composition. The empty space between drums and the one between drums and sided walls of the container can be in filled with cement based mortar containing radioactive materials. It is recommended to be added only a small quantity of NA in the mixture, so as the radioactive material volume should not increase substantially before mixing it with the binder. The binder can be a mixture of sand, aggregates and cement, silicate, ash and plasticizer. It is recommended that both mixing and the dispersion of the radioactive material should be made in the binder, so this will make a matrix which contains and strongly binds discrete pieces or particles of radioactive material.

R. S. Kingsley [17] have proposed also a method for minimizing the volume of radioactive waste and for using RCA in manufacturing prefabricated items (containers, cells and vaults for final disposal of waste in near surface disposal facilities, beams and segments for construction of depth geological disposal facilities). Concrete is the only material compatible with clay formations, which can be used for reinforcing tunnels and excavated galleries. In Spain it was studied [21] the use of recycled crushed radioactive concrete for manufacturing concrete prefabricated (beams and segments) used for building a deep geological disposal facility in clay formations. It was estimated that will be necessary about 58,500 tons/year of prefabricated concrete. During operating period of the disposal facility, the necessary amount of prefabricated will be of about 3,300 tons/year. Considering that the radioactive rubble used in the concrete composition will be of about 60 % wt., it is estimated that the total amount of recycled radioactive rubble will be of about 97,000 tons. The evaluation of this method shows that recycling of radioactive concrete for manufacturing prefabricated items is feasible and less expensive than near surface disposal facility.

3.1.4. Radioactive concrete as infilling, completing or encapsulating materials

3.1.4.1. C. Koichi method

Conventionally [22], long term disposal of low level waste is made in 200 litters steel drums, placed horizontally in large parallelepiped concrete pit. The gap between the steel drums is filled with sand, and the upper part is covered with a concrete lid, to preventing direct contact between waste drums and rain water or groundwater. In Japan, the concrete estimated to arise from decommissioning process of a nuclear power plant (one reactor) exceed 500,000 tons, from which about 5,000 tons are of radioactive concrete. If this quantity is introduced in 200 litters drums, assuming in each drum can be placed 200 kg, only by this radioactive concrete will result 25,000 solid waste packages which requires long term monitoring. Because the number of waste drums generated yearly in Japan is up to 50,000 pieces, representing half of the total amount of radioactive waste resulted in a year, this is clearly a problem.

An **innovative** solution to this problem was proposed by C. Koichi [22] which use radioactive concrete as infilling material for the radioactive waste drums, for efficient disposal in safe conditions of radioactive concrete resulted out of decommissioning process of nuclear facilities. Following similar disposal conditions as the conventional method, the author proposed replacing the natural aggregates sand used as infilling material, with a mortar based on radioactive concrete. The concrete is crushed to a granulation ≤ 5 mm, than mixed with hydraulic cement, than supplementary added water, until obtaining a paste. The paste it is introduced by compression in the gap between drums, for radioactive waste solidification, without placing it inside the drums. Also, even if groundwater seep the pit, due to the protection that concrete gives to the solidified packages, the contact between those and the water is at minimum, reducing drastically radionuclide leakage. Due to the fact that by the proposed method it becomes possible using radioactive material as infilling material for the spaces between the steel drums pre-placed in disposal enclosures, it is not necessary to use the drums for disposing inside them the above mentioned radioactive concrete. A similar method is applied at El Cabril (Spain) [23, 24]. In a rectangular reinforced concrete containers (11 m^3), there are placed 18 drums of 220 l filled with LLW/ILW. The drums are fixed by injecting in the empty space between them mortar containing radioactive aggregates. In this way, 50 % of the sand volume is replaced with recycled radioactive concrete fine aggregates. Each year, at El Cabril there are recycled about 700 tons of crushed concrete.

3.1.5. Radioactive concrete as mortar for immobilizing LLW waste

3.1.5.1. K. Yamamoto method (1)

Conventionally [25], when a nuclear power plant **101**/ reprocessing facility **102,** is decommissioned radioactive waste **103** results (Fig. 1). After crushing, radioactive concrete waste **105** is mixed with infilling mortar **108** made of NA, which is poured into the drums **110** and left for solidification. The drums **110** are placed in a reinforced concrete pit, embedded in concrete made of NA and final disposed.

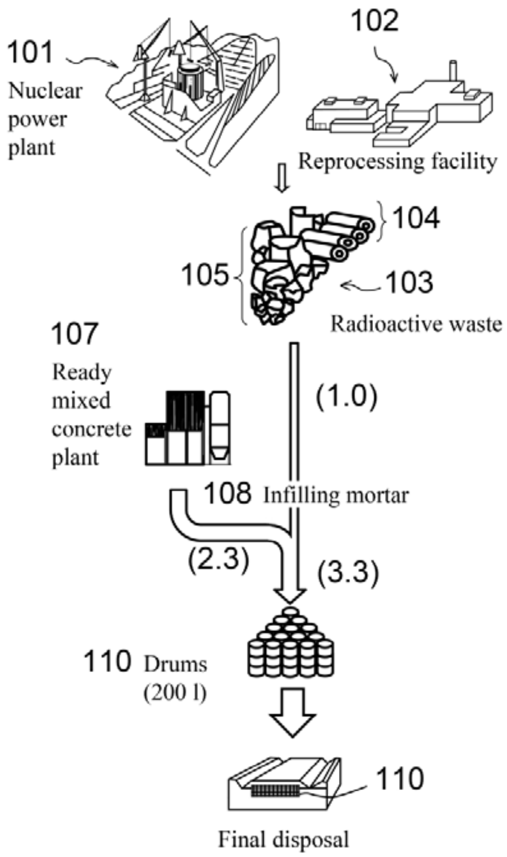

Fig. 1 – Classic method for radioactive concrete processing (referenced from [25]): 101 – nuclear power plant; 102 – reprocessing facility; 103 – radioactive waste; 104 – steel bars; 105 – radioactive concrete; 107 – ready mixed concrete plant; 108 – infilling mortar; 110 – drum.

Disadvantages of conventional method:

– produces an amount of waste final disposed of about 3 times larger than the amount of radioactive waste arise from the decommissioning process;
– it can be produced a leak of radioactive material from the drum into the ground and into the groundwater, extending the contamination and creating the need for repackaging the radioactive material, in case of protection deterioration of the pit or on the drum, in a short period of time.

K. Yamamoto *et al.* [25] have proposed an **innovative method** for processing and final disposal for radioactive concrete waste, which ensures:

- inhibition of spreading radioactive contamination by deteriorating the protection of the pit/drum;
- decreasing the amount of waste for final disposal as well as the disposal space.

The residues of radioactive concrete are conditioned by crushing/grinding process in different granulometric fractions, mixed and compacted by vibration into the drums. Using of a continuous particle size distribution ensures a better filling of the space than using large size particles, reducing substantially the waste volume.

By modifying the ratio of granulometric fractions added in the mixture it can be defined a field in which the movement between particles comes to a minimum and the compaction density is great. The fine fraction is used as solidification material for the coarse fraction. By the fact that in the mixture it is not introduced any external solidifying material, the volume of waste after processing it is significantly decreased. In case that, during long term disposal, groundwater seep the waste drums, it will be consumed by hydrating the mixture, and so the spreading of the radioactive contaminant is inhibited.

3.1.5.2. S. Mitsuaki and O. Masamichi method

The method [26] aims to ensure:

- treating of concrete radioactive waste by reusing all debris resulted in the crushing process;
- manufacturing of filling mortar for solidification of other radioactive waste, using fine aggregates and a chemical admixture.

The authors have proved that modifying the amount of chemical mixture and the specific surface of the fine fraction, will determine a modification of the properties for fresh and hardened mortar, such as:

- modifying granulometric distribution of fine aggregates to a maximum dimension of 2.5 mm, from which a 10% fraction – which passed through a 0.15 mm sieve with a density of 2.6 g/cm^3, leads to a fluidity and compression strength comparable with same properties of the mortar obtained from NA;
- increasing the fraction of chemical mixture in the mortar leads to:
  - decreasing the mortar fluidity;
  - increasing the compression strength of the solidified mortar;
- increasing specific surface of the fine fraction in the mixture determine a light decrease of the fresh mortar fluidity, and a strong deterioration after 30 minutes.

Reusing radioactive concrete waste as a solidification material for other radioactive waste will lead to decreasing of the costs for final disposal, compared to a simple conventional disposal of radioactive concrete waste.

3.1.5.3. H. Ueki method (1)

Conventionally (Fig. 2), the concrete is cut as blocks using water jet or diamond wire cutting devices. **2**. During cutting operation water is used as cooling agent and result an amount of concrete slurry **3** (Fig. 2a). The sludge containing a large amount of water (50÷70%) is being dried in a sedimentation-filtration dehydrator **4** till a sludge consistence (dehydrated sludge **5**) (Fig. 2b). The dehydrated sludge **5**, is mixed with cement **6** and water **7** in a mixer device **8** (Fig. 2c and d). The resulted mortar is poured in the steel drums and solidified as a homogenous body **9** (Fig. 2e).

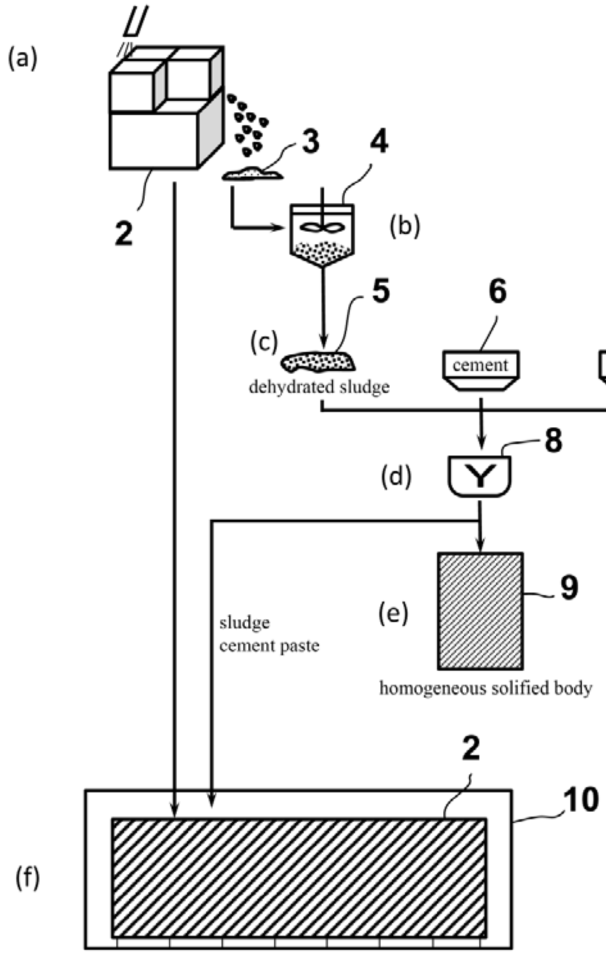

Fig. 2 – Classic method for radioactive concrete processing (referenced from [27]):
2 – concrete block; 3 – concrete sludge; 4 – sedimentation-filtration dehydrator; 5 – dehydrated sludge; 6 – cement; 7 – water; 8 – mixer; 9 – homogeneous solidified body; 10 – container.

The innovative method developed by H. Ueki *et al.* [27] is proposing the processing of radioactive sludge resulted from concrete cutting operation as pellets, and their final disposal in the containers together with the concrete blocks and pieces, reducing the total volume of radioactive waste. In the first phase of the process, from the demolished concrete structure, it is being cut a concrete block using a diamond wire, having dimensions and shape suitable for introducing it in the container and for injecting the filling material. In the second phase, the sludge resulted during cutting operations is being dried in a centrifugal filter press type dehydrator, till a humidity of about 30÷55%. In the third phase, the dehydrated sludge is mixed with cement and shaped as cylinder type pellets. The proportion between cement and water must be correlated with the water content within the sludge (≥ 0.6) for obtaining a compression strength that can allow manipulation of the pellets without deterioration. In the fourth phase, the fresh pellets are left to harden at about 20^0 C, but not to dry, for avoiding occurrence of cracks and for inhibiting water absorption. In the fifth phase, the concrete block is placed inside the container on special supports, for ensuring equal space on all sides. In the sixth phase, the pellets are placed in the space between the container's inner walls and the concrete block. In the seventh phase, in the empty spaces between the pellets is injected filling mortar, which must fulfill the condition of fluidity p-cone 16÷50 seconds.

The upper opening of the container is covered and sealed, and so the radioactive concrete waste is ready for the final disposal. By applying the above proposed method it will not be generated any independent concrete sludge, and also it will contribute to a decrease of the radioactive waste volume inside the package containing the radioactive concrete block, radioactive concrete rubble and the whole quantity of concrete sludge.

3.1.5.4. H. Ueki method (2)

Conventional method for treating concrete sludge is presented in 3.1.5.3. The **innovative method** developed by H. Ueki *et al.* [28] is proposing to process the radioactive sludge resulted during concrete structures cutting operations and its final disposal into the containers, along with other concrete blocks and pieces, decreasing significantly the radioactive waste volume. The proposed method is not using radioactive sludge as solidified homogenous body, instead is decreasing the radioactive waste volume inside the package containing the radioactive concrete block, radioactive concrete rubble and the whole quantity of concrete sludge. In the first phase of the process (Fig. 3a), from the concrete structure that will be demolished it will be cut with a diamond wire **11,** using water as cooling agent, a concrete block **12** with desired dimensions and shape. In the second phase, the concrete sludge **13** resulted, which contains a significant quantity of water, is being dried in the centrifugal filter press type dehydrator **14** resulting dehydrated sludge **16** which can be easily processed as waste (Fig. 3b). The dried concrete sludge **13** contains about 30–40 % weight water. In the third phase is prepared the first mortar composition **18,** by mixing the dehydrated sludge **16** and water reducing agent **17** (Fig. 3c and d). In the first mortar **18** is being added the binding material (cement) **19**, for increasing the mortar strength. The necessary quantity of binding material depends on the water content inside the dried concrete sludge. The authors mention that the proportion between cement and water must be correlated with the water content inside the sludge (≥0.6) for obtaining a compression strength that will allow manipulation of the pellets without deteriorating them. In the fourth phase, it is obtained the solidified body 22 by injecting, on the upper part of the container, the first mortar **18** (Fig. 3f). The inner part of the container can be filled with debris **23** resulted during radioactive concrete cutting operations. In the fifth phase, for obtaining the second mortar **29** are being mixed: dehydrated sludge **16**, cement **24**, sand **26**, water **27** and chemical admixture **28** (Figs. 3g and h) in the following ratios:

– water-cement 0.4÷ 1.0;
– sand-cement 1.0÷2.9;
– sludge between 0÷35 % wt. from total amount of sand and sludge;
– chemical admixture ≥ 2 % wt. from total amount of cement and sludge.

As sand **26** added to the dehydrated sludge **16** it can be used: water sand, natural sand, crushed sand or crushed concrete, sorted and used as fine recycled aggregates. By using a high performance water reducing agent and by adding an amount of ≥ 2 % wt. of the total amount of cement and dehydrated sludge, it can be increased the mortar fluidity. In the sixth phase fluidity is checked for the second mortar **29** (Fig. 3i). In the seventh phase, the container **21** which contains solidified material **22** is being placed in the outer container **34,** having inner dimensions which allow placing the container **21** on supports **34a**, making a second gap **34d**. First gap **34c** between sided walls of the inner container **21** and outer container **34** is filled with debris **36** (Fig. 3j) obtained from concrete structure cutting. In the eighth phase, in the remained space it is injected and solidified the second mortar **29**. The cover **34b** of the outer container **34**, is being covered with a sealed lid, and then the container is disposed as solid radioactive concrete body (Fig. 3k). Concrete debris **23** may be ground finely and mixed in concrete slurry **13**. Depending on the size of the inner container in the outer container can accommodate 2 to 3 pieces of inner containers.

3.1.5.5. Y. Tsukahara method

The **innovative method** developed by Y. Tsukahara et al. [29] is proposing to ensure:

– decreasing the price for:
  - final disposal of concrete waste;
  - transport from treating place to the incorporation place;
– increase of disposing density for radioactive concrete waste;
– simultaneous final disposal for waste cutting fluid and for high content of solid and calcium carbonate generated as secondary waste.

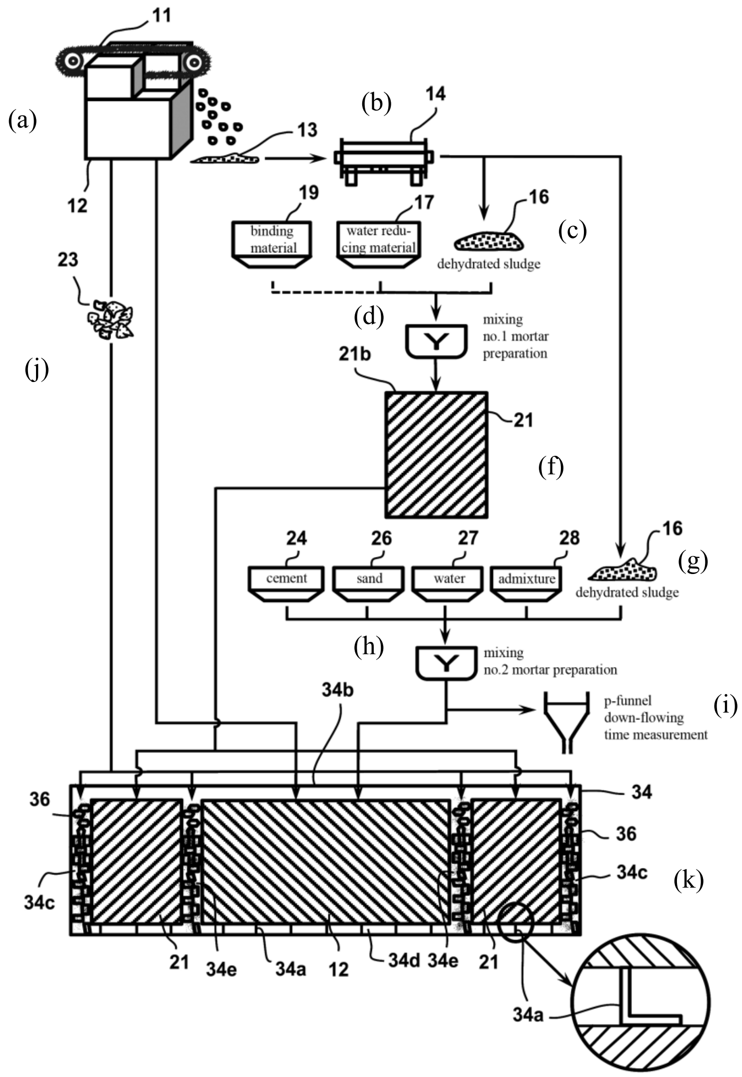

Fig. 3 – Innovative method for radioactive concrete processing (referenced from [28]): 11 – mechanical cutting device/ water jet cutting device; 12 – concrete block; 13 – concrete sludge; 14 – sedimentation-filtration dehydrator; 16 – dehydrated sludge; 17 – water reducing agent; 19 – binding material; 21 – inner container; 21b, 34b – opening; 23 – debris; 24 – cement; 26 – sand; 27 – water; 28 – admixture; 34 – outer container; 34a – two or more supporting projections; 34c – 1st gap; 34d – 2nd gap; 34e – 3rd gap; 36 – concrete package.

From the radioactive concrete walls of a decommissioned structure, are being cut large blocks with dimensions suitable for fitting in the final disposal box shaped container. The large blocks, with maximum dimensions of 1800 mm × 3200 mm × 1100 mm high, are cut with diamond wire in three smaller blocks with 600 mm width, so they can be easily stored in the final disposal container. Two of the smaller blocks are placed in the manipulation container, trying to maintain an equal 100 mm free space on both sides. In this empty space are placed large aggregates, with dimensions of about 15÷50 mm. The fraction ≤ 15 mm is being re-crushed to dimensions of about 2.5 mm, and used as fine aggregates to the mortar composition. The mortar is poured to fill the spaces between the large aggregates. In this way, in a 5 m^3 manipulation container containing 4.1 m^3 radioactive wastes, the filling degree becomes about 84 %. In addition, as fine aggregates for the mortar, can be used:

– solid content resulted in diamond wire operations, separated from the cooling fluid during a dehydration treatment as recyclable concrete sludge;
– calcium carbonate resulted by CO_2 bubbling, separated from the cooling fluid during a dehydration treatment on a press filter, as recyclable calcium carbonate sludge.

The sludge's are reused as fine aggregates, in the mortar composition.

3.1.5.6. T. Kazuyoshi method

Conventionally [30], in the first phase, the concrete is crushed resulting large diameter aggregates and powder. After adding water and cement over them, the ingredients are mixed, and the resulted mixture is poured into the drums. The radioactive package is formed inside the drum, due to the water and cement hydrating reaction, and it is final disposed in reinforced concrete pits. The conventional method requires a big disposing space for the conditioned waste.

The **innovative method** [30] is proposing to ensure a treatment of the radioactive concrete in order to increase the volume of the crushed concrete into a volume unit of a formed radioactive waste block. The radioactive concrete resulted from dismantling and demolishing operations, is crushed in a jaw crusher, obtaining large and fine aggregates and powder. The granular material is sorted on the three categories: large aggregates (> 2.5 mm), fine aggregates (0.15 ÷ 2.5 mm), and powder (< 0.15 mm).

Then, fine aggregates are mixed and heated at 700÷ 800^0C so the powder could gain self-hardening properties. Fine aggregates, powder and water are mixed in a mixer, and the mixture is poured over the large aggregates pre-placed in a drum. Optional, large aggregates and mixture can be poured into the drum in the same time. The composition within the drum is hardening, because water and treated powder determine a re-hydration reaction (hardening process). The newly formed packages, containing large aggregates, fine aggregates and self-hardening powder are transported in the near surface disposal facilities. It is noted that adding cement in the composition is not necessary for hardening, in case the package is formed out of crushed radioactive concrete, so the amount of crushed radioactive concrete in a package volume unit can be increased. The cost of final disposal for the radioactive concrete arise from decommissioning activities becomes insignificant. As alternative, by initial separation of the powder from the other fractions, along with separate thermal treatment, workability of the mortar can be improved. The applicability of the method can be extended to final disposal of metallic waste. In this case, the filling material is made only with fine aggregates, self-hardening powder material and water.

3.1.5.7. K. Yamamoto method (2)

Conventional method is the same with the one presented in 3.1.5.1.

K. Yamamoto et al. [31] have proposed an **innovative method** for processing and final disposal of radioactive concrete waste arise for decommissioning activities, which ensures reducing of the volume of final disposed waste and, by default, the disposal space. In the first phase (Fig. 4), radioactive waste is sorted by categories: concrete waste and other waste (rebar).

The concrete waste are crushed in a crusher and sorted as:

– fine granulometric fraction **6** (≤ 5 mm);

– large granulometric fraction **7** (≥ 5 mm).

In the second phase, fine granulometric fraction is grounded in a heated mill, till powder stage. After grounding, the powder particles have dimensions suitable for a specific surface area of 1.000÷ 5.000 cm^2/g. In the third phase, the powder is mixed with a specific amount of water in a mixer and result a cement paste infilling material. In the second phase, along with the very fine fraction, it can be grounded also the slag, resulting a very fine powder that improves the initial properties. In this case, in the third phase, when water is added it appears a hydrating reaction by which the cement paste improves strength of the infilling material which solidifies in the drum the large dimension fraction. In the fourth phase, the large granulometric fraction with particles ≥ 5 mm is pre-placed in the drum along with the crushed reinforced concrete. Inside the drum is added the cement paste, the large granulometric fraction being completely solidified. The drums are placed in a reinforced concrete shelter and embedded in concrete. Above the concrete is placed earth and sand, and so the wastes are considered to be final disposed.

3.1.6. Radioactive concrete as mortar for waterproofing

Serge Berthouly [32] have developed a method for using radioactive concrete arise from the decommissioning process of very low level concrete waste < 100 Bq/g, at long term disposal of radioactive and toxic waste. The proposed method has the following phases:

– separation of the concrete blocks and debris (0 ÷ 500 mm) from the rebar;

– crushing:
  - with a jaw crusher, the concrete blocks and/or debris (0÷500 mm) till dimensions < 200 mm;
  - with a rotary crusher, the material < 200 mm, till a granulation < 20 mm, with re-crushing of the debris > 20 mm;

– transport of the crushed material in storing silos;

– mixing the crushed material < 20 mm with self-leveling cement;

– drilling of injection shafts above the underground cavity;

– waterproofing of the underground cavity walls by injecting fluid cement, precisely at the contact with the delimiting walls;
– closing the injection shafts by filling them at a predetermined level with sand or hydraulic concrete.

3.1.7. Building of new installations

Crushed concrete aggregate will be reused and recycled on Sellafield Site [33] mainly for:
– non-structural purposes such as mass concrete fill, support for hard landscaping (*e.g.* Calder Cooling Tower basins, mass concrete, road sub-base, screeds and fill);
– sealine concrete covers.

3.2. STATUS OF TECHNOLOGY AT NATIONAL LEVEL

Currently, in Romania LLW radioactive concrete waste are pre-placed, as concrete blocks, in 220 l cylinder shaped carbon steel drums, and then solidified with mortar (mixture made of fine aggregates obtained from natural resources, cement and water), to ensure a specific strength of the package that will be final disposed. The conventional technology offers a filling proportion of about 50 % vol. for the radioactive concrete in each waste container. Most part of the radioactive waste arise form decommissioning activities is final stored in this way. So far, there was no constraint for developing, at national level, a technology for recycling the radioactive concrete, but starting 2013 the ongoing decommissioning process of the VVR-S Nuclear Reactor will produce large amounts of concrete waste (975 tons, from which 75 tons of concrete LLW). In these conditions, a proposal of an innovative technology is absolutely necessary.

3.3. COMPARATIVE ANALYSIS OF RECYCLING TECHNOLOGIES FOR RADIOACTIVE CONCRETE

The recycling methods for radioactive concrete developed so far have similarities but also differences regarding:
– types of equipment used in the crushing process;
– the parameters of the crushing process;
– number of crushing phases;
– type of the final product (shielding, prefabricated pieces, mortar, etc.);
– characteristics of the recycled fine aggregates, used for obtaining the final product.

Taking into account the low cost involved, all the methods are financially attractive. It was always pointed that the use of recycled concrete in other way than for obtaining the mortar necessary in conditioning the waste in the drums will be limited. The radioactive concrete recycling has a greater economic impact versus industrial concrete waste recycling (as an example, the approximate cost of LLW final disposal is about 5,000÷ 8,500 USD/ mc [34]). Compared with radioactive steel recycling technology, radioactive concrete technology is cheaper, more portable and with a bigger availability [19], but demands supplementary actions in order to fulfill the increased safety requirements.

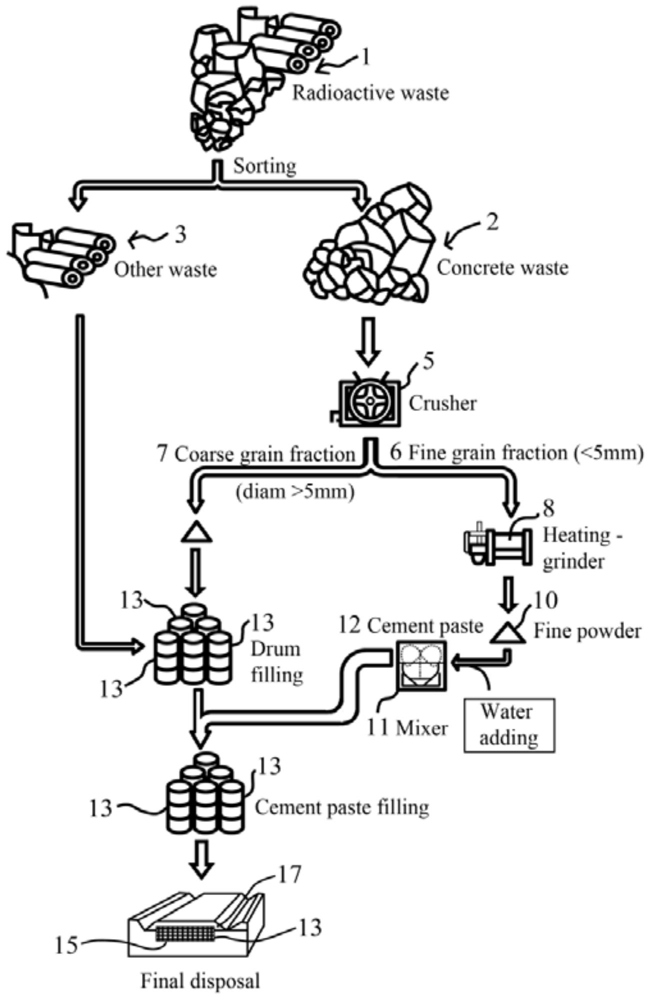

Fig. 4 – Innovative processing method and disposal of radioactive concrete waste referenced from [31]: 1 – radioactive waste; 2 – concrete waste; 3 – waste, such as a steel frame; 5 – crusher; 6 – fine grained fraction; 7 – coarse grained fraction; 8 – heating grinder; 10 – fine powder; 11 – mixer; 12 – cement paste; 13 – drum; 15 – concrete pit; 17 – earth and sand.

The necessary methods for reducing dose exposure of the workers to radioactive dust can be easily ensured. The analysis of the economic data made for using crushed recycled concrete for manufacturing containers or as infilling material, shows that the concrete generated in EC can be recycled, and result a decrease of costs for near-surface and depth disposal facilities. Recycling technologies cannot be simply evaluated; their utility and applicability must be correlated with:

– existence and possibility for design and construction of radioactive waste final disposal facilities;
– repository type (near surface or depth);
– applicable legal requirements the free release of material in the nuclear field;
– public acceptance.

Necessity of implementing an innovative technology at national level is resulted out of following constraints:

– there is no market demand for radioactive concrete shielding or for prefabricated pieces used in strengthening of galleries or depth tunnels, because there is available only one near-surface disposal facility;
– small number of existing nuclear facilities does not require a significant number of concrete shielding;
– legal requirements do not allow using radioactive materials for road foundations and untrammeled embankments mixture with homogenous granulometry, infilling material or as aggregates for manufacturing new concrete;
– public acceptance is limited towards building new nuclear facilities, and slightly increased towards upgrading the existing ones;
– applying the recycling methods and minimizing the waste volume in the site meets public expectations regarding waste recycling strategies.

IFIN-HH has on its site a VVR-S type nuclear reactor being in the first decommissioning stage, a radioactive waste treatment facility and a national near-surface disposal facility- Baita Bihor. Currently, radioactive waste is conditioned in 220 l carbon steel drums. Being a significant radioactive waste producer, most of them arise from the decommissioning process. IFIN-HH has as first responsibility the management of those wastes, by developing new waste recycling technologies.

4. CONCLUSIONS

It is now widely accepted that there is a significant potential in exploitation and recycling of the radioactive concrete arise from nuclear installations decommissioning, and for using it in added value applications in order to maximize environmental and economic benefits. The analyzed methods confirm the applicability of the technologies that use radioactive concrete for:

– manufacturing:
- radiological protection ;
- containers for processing, isolating, final disposal or storage radioactive waste or dangerous materials;
- concrete prefabricated;

– preparing:
- immobilizing material for radioactive waste drums;
- mortar for immobilizing (solidifying) other low level solid waste;
- mortar for waterproofing;

– building of new nuclear facilities under certain conditions.

Recycling of concrete waste volume reduction by applying innovative technologies imply:

– increasing of recycled waste resources;
– decreasing of the final disposed waste amount;
– decreasing of final disposal waste cost;
– increasing of safety for disposed packages.

The properties of concrete obtained from recycled aggregates are influenced by the aggregates used through geometric characteristics, the thickness of the mortar layer adhered to RCA, the strength of the demolished concrete, the degree of replacement of natural aggregates, the use of fine or large aggregates etc.

It is very important to be precisely determined the properties of the RCA (water absorption and density) before using them, for avoiding big variations in hardened concrete properties, as well as for obtaining fresh concrete with proper workability, stability and cohesion. There are not technologies with general application. The applicability is conditioned by the specific national requirements.

The advantages of radioactive concrete waste recycling strategy include: saving money, reducing of carbon dioxide emissions, reducing of waste volume and saving of natural resources.

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