BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

IN THE MATTER OF:	)	
	)	AS 2021-001
Midwest Generation, LLC's Petition for	)	
an Adjusted Standard and Finding of	)	
Inapplicability from 35 Ill. Adm.	)	
Code 845 (Joliet 29 Station)	)	
	)	

To: See attached service list.

NOTICE OF ELECTRONIC FILING

PLEASE TAKE NOTICE that I have today filed with the Office of the Clerk of the Pollution Control Board **ILLINOIS EPA'S CLOSING BRIEF** on behalf of the Illinois Environmental Protection Agency, a copy of which is herewith served upon you.

Respectfully submitted,

Dated: September 13, 2022

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY,

Respondent,

BY: /s/Stefanie N. Diers
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THIS FILING IS SUBMITTED ELECTRONICALLY

BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

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Midwest Generation, LLC's Petition for an Adjusted Standard and Finding of Inapplicability from 35 Ill. Adm. Code 845 (Joliet 29 Station)	)))))	

ILLINOIS EPA'S CLOSING BRIEF

NOW COMES the ILLINOIS ENVIRONMENTAL PROTECTION AGENCY, ("Illinois EPA" or "Agency") by and through its counsel and submits its Closing Brief in the above captioned case. Illinois EPA states as follows:

I. BACKGROUND

1. On April 15, 2021, the Board adopted new regulations providing standards for disposal of Coal Combustion Residuals ("CCR") in surface impoundments at 35 Ill. Adm. Code 845 ("Part 845"). *See* Board Docket R2020-019. The Part 845 rules became effective on April 21, 2021. 45 Ill. Reg. 5884 (May 7, 2021).

2. On May 11, 2021, Midwest Generation, LLC ("MWG") filed a petition for an adjusted standard from 35 Ill. Adm. Code §845.740(a) and a finding of inapplicability of Part 845 for certain impoundments located at its Joliet 29 Station ("Petition"), in which it requested a hearing on its petition.

3. The Petition concerns three surface impoundments, which Petitioner designates as Pond 1, Pond 2, and Pond 3.

4. Specifically, Petitioner is seeking the following adjusted standards from the requirements contained in Part 845:

a. Pond 2: MWG seeks an adjusted standard to allow the decontamination and retention of the existing liner rather than the liner's removal as required for closure by removal in Section 845.740(a).

b. Pond 1 and Pond 3: MWG asserts that Pond 1 and Pond 3 do not satisfy the regulatory definition of a CCR surface impoundment and seeks an adjusted standard finding that Part 845 of the Board's regulations is inapplicable.

5. On August 22, 2021, Illinois EPA filed with the Board its Recommendation as to Petitioner's request for a finding of inapplicability of Part 845 to Pond 1 and Pond 3.

6. On February 4, 2022, the Agency filed its Recommendation addressing Pond 2 and Petitioner's request for an adjusted standard from Section 845.740(a).

7. On June 28, 2022, and June 29, 2022, the Board held hearings with respect to only Pond 2 for an Adjusted Standard.

8. On July 27, 2022, the hearing officer issued an Order addressing the briefing schedule. Briefs in this matter are due by September 13, 2022. Response Briefs are due by October 7, 2022.

II. ARGUMENTS

Petitioner has the burden of proof in an adjusted standard case. 415 ILCS 5/28.1(c). Therefore, Illinois EPA does not have to provide a single piece of evidence or testimony and the Board could still deny Petitioner's request for an adjusted standard. All that is required of Illinois EPA is the recommendation, which was filed on February 4, 2022.

In this case, the Petitioner has failed to meet its burden of proof under Section 28.1(c) of the Environmental Protection Act ("Act"). Since 35 Ill. Adm. Code § 302.122(b) does not provide a specific level of justification required by a petitioner to obtain an adjusted standard, the level of the justification requires Petitioner to present adequate proof of the following under Section 28.1(c) of the Act:

(1) factors relating to that petitioner are substantially and significantly different from the factors relied upon by the Board in adopting the general regulation applicable to that petitioner;

(2) the existence of those factors justifies an adjusted standard;

(3) the requested standard will not result in environmental or health effects substantially and significantly more adverse than the effects considered by the Board in adopting the rule of general applicability; and

(4) the adjusted standard is consistent with any applicable federal law.

If any one of the four elements have not been adequately proven, the Board must deny the adjusted standard. In this case, Petitioner has failed to meet the four factors. Therefore, Petitioner's request for an adjusted standard request must be denied.

1. **Petitioner's adjusted standard petition should be denied because the factors relating to both Petitioner's reuse of the liner are not substantially and significantly different from the factors relied upon by the Board in adopting the general regulation applicable to Petitioner.**

The factors the Board relied on in adopting 35 Ill. Admin. Code 845.740(a) include (1) impact of contaminated subsoils on human health and the environment. *See* Agency Recommendation filed February 4, 2022. In this case, the Petitioner argues that the current liner only needs to be decontaminated on the surface. The Illinois EPA maintains that the poz-o-pac, black silty gravel and HDPE liner require further analytical testing to ensure that impacts to the environment are not occurring and have been mitigated for further use as a liner system at Pond 2. Analytical data is required to determine the following: the potential for the poz-o-pac to leach heavy metals from the CCR it is comprised of; the potential for the black silty gravel to leach heavy metals and the nature of its composition; and the integrity of the HDPE to verify the competency of the liner seams. The aforementioned is detailed in the following subsections:

a. Poz-o-pac

As exhibited in the History of Construction for Pond 2, the poz-o-pac, is comprised of fly ash and bottom ash (Rec. Ex. D Att. 3, App. A-2, Drawing No. 5079C5019). While Mr. Radlinski, MWG's poz-o-pac expert, explained the pozzolanic reactions that occur when fly ash, bottom ash, lime and water are mixed, he did not address that the poz-o-pac has the tendency to degrade and crack over time or whether the poz-o-pac at Joliet 29 Pond 2 is currently degraded and cracking, 44 years after mixture and placement.

Furthermore, in Mr. Radlinski's expert opinion and testimony, he did not testify that the metals will alter permanently to another elemental form that is inert. According to Gluchowski, et al (2018) poz-o-pac, much like recycled concrete discussed further below, contains heavy metals from the fly ash and bottom ash at the time of mixture, are likely still within the poz-o-pac currently, unless it has degraded and leached the metals into the groundwater, or it has the potential to degrade and leach into the groundwater in the future. See Attachment 1, Gluchowski, et all (2018).

During Ms. Gale's direct questioning of Mr. Radlinski she asked him the following question:

> **Q. So earlier you said you disagreed with the Agency's conclusions that the Poz-O-Pac falls within the definition of CCR. Can you explain why?**
>
> A. Yes, certainly. In simple terms calling Poz-O-Pac a CCR, a coal combustion residual, would be like calling Poz-O-Pac fly ash. That's what CCR is, right. So it's like Poz-O-Pac, but calling Poz-O-Pac slag, of course either one of those statements would be true or technically correct because, as I explained, fly ash is a really fine powder. Slag is aggregate size particles, and Poz-O-Pac is a composite construction material consisting of a cementitious paste that glues in this case boiler slag with other particles. We're talking about completely different things. So maybe make a little different analogy, it would be like calling concrete cement only because cement is used to make concrete or make another analogy be like calling cake flour because flour is used to make cake. Obviously, again, those statements would not be true because you can't really move cement out of concrete once it's there much like I don't think you can remove flour from the baking out of a cake. So for same reasons you cannot remove fly ash out of Poz-O-Pac. T. June 28, 2022, Page 76-77 line 7.

In his response above, Mr. Radlinski did not address whether the heavy metals in fly ash and bottom ash could leach from the poz-o-pac when it degrades. In the questions from the Board, Mr. Radlinski addressed the similarity of poz-o-pac, cement, and concrete as follows:

> **MR. RAO: Are you aware of any studies over the last maybe 15, 20 years, where they've done leachate studies to show that once, you know, fly ash is used in the pozzolanic reaction and becomes Poz-o-Pac, that it won't leach the chemical that it used to have?**
>
> THE WITNESS: Specific—not as it relates to Poz-o-Pac, in fact not even as it relates to fly ash concrete or concrete containing fly ash…..there are literally thousands of miles of concrete pavements in the United States and worldwide, concrete with—you know, pavements with—made with concrete fly ash, and it's just not a—they get a lot of rain and otherwise precipitation, a lot of exposure and potential for leaching, and to my knowledge it's just not a concern. T. June 28, 2022, P. 85-86.

Although Mr. Radlinski states that he is not aware of studies in the last 15 or 20 years that relate to the pozzolanic reaction or concrete containing fly ash not having the potential to leach heavy metals, the Illinois EPA found that a study published in Applied Sciences in 2018, shows recycled concrete comprised of fly ash leaches heavy metals such as cobalt, cadmium, sulfates, and chlorides. See Attachment 1, Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering (2018).

The study, Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering (Gluchowski, et. Al, 2018, p. 15) did not test for all metals commonly found in fly ash, but it did find that select fly ash heavy metal constituents do leach from the broken-down concrete. Based on Mr. Radlinski's testimony, concrete and poz-o-pac are elementally similar as follows:

> **MR. RAO: It kind of answers my question, but my follow-up would be elementally they may be same, but how is the Poz-O-Pac different in terms of once it's undergone the reaction and becomes Poz-O-Pac, is it a substance or a compound that's nonleachable or what's the difference?**
>
> THE WITNESS: Excellent question, yes, a very important point. The calcium silicate hydrate which is the product of the pozzolanic reaction is a non -- is a water insoluble material. And, in fact, it's the exact same chemical compound that forms from the hydration or reaction of Portland cement and regular concrete. If you mix, you know, if you get a bucket and put it -- buy the cement, Portland cement from Home Depot, dump it in the bucket, put some water and rock and sand, mix it up and give it a few hours. And, you know, next day if you were to look at -- try to determine the chemical composition of the -- of course not the aggregate, but the grade, the paste, the hard cement paste, it will be primarily calcium silicate hydrate as well, which obviously is insoluble, and, you know, as demonstrated by the fact that we have, you know,

> concrete structures going back centuries that work well and when exposed to water and even when immersed in water. T. June 28, 2022, P. 84-85.

The Illinois EPA maintains, that based on Mr. Radlinski's testimony, the Illinois EPA's Recommendation and the aforementioned study, there is a potential for heavy metals leaching from the poz-o-pac.

The study focused on the ability of the concrete, once broken down into gravel, sand and silt sized particles for use as an aggregate, to leach heavy metals and its hydraulic properties such as permeability. The study only performed chemical analyses for cobalt, cadmium, copper, nickel, lead, zinc, sulfates, chlorides, carbon, and pH. Of those heavy metals, cobalt, cadmium, copper, nickel, sulfates, carbon, and chlorides were detected. Table 5 of the study compared leachate results to different standards than those in 35 Ill. Admin. Code 845.600, but the minimum detection limits were less than 35 Ill. Admin. Code 845.600 Groundwater Protection Standards (GWPS) which enabled the Illinois EPA to compare the study results with 845.600 GWPS. (Attachment A, P. 15, Table 5). It should be noted that 35 Ill. Admin. Code 845.600(a)(1) does not require monitoring for copper, nickel, zinc, and carbon. However, the Illinois EPA focused on cobalt results from the study because cobalt exceeds 35 Ill. Admin. Code 845.600(a)(1) at Pond 2 at the downgradient well, MW-04, is detected in MW-03 and MW-05, and not detected at the upgradient well, MW-10. Table 5 of the study revealed that cobalt leached from crushed concrete at levels above 35 Ill. Admin. Code 845.600(a)(1) GWPS. This is a concern that Illinois EPA argues must be addressed before an adjusted standard is granted by the Board.

Furthermore, none of the witnesses could attest to the poz-o-pac having been tested for its leaching properties when it degrades or is broken down. Mr. Maxwell described the groundwater monitoring system as being consistent with the requirements of Part 257. (TR, June 28, 2022, Pgs. 104-105). Mr. Maxwell stated that Cobalt occurs above groundwater protection standards only in MW-4.

(TR, June 28, 2022, P. 118). Cobalt is one of the constituents that must be monitored at CCR surface impoundments under both Part 257 and Part 845. Mr. Maxwell also provided an explanation of how chlorides, such as those found in road salt, can cause leaching of Cobalt when it is present in soils through the process of ion exchange and that Cobalt occurs in the soils in Illinois. (TR, June 28, 2022, P. 125-127). Mr. Maxwell concluded that ion exchange is causing the presence of Cobalt at MW-4 at Pond 2. (TR, June 28, 2022, Pg. 128). During cross examination, Mr. Maxwell stated that Cobalt has not been detected in MW-10 and that MW-10 is down gradient of Route 6. (TR, June 28, 2022, P. 166). When looking at Mr. Maxwell's statements one may logically conclude: 1) To be consistent with Part 257 (or Part 845) the groundwater monitoring system around Pond 2 detects the background quality of groundwater unaffected by a CCR surface impoundment, as well as groundwater quality that has passed the down gradient waste boundary of a CCR surface impoundment. 2) Because MW-10 and MW-4 are both down gradient of Route 6, which is the source of chloride bearing road salt causing ion exchange, the soil up gradient from both MW-10 and MW-4 are subject to the same ion exchange process. 3) Cobalt is not detected in MW-10, but Cobalt exceeds the groundwater protection standard in MW-4. 4) Pond 2 lies between MW-10 and MW-4, with MW-10 up gradient of Pond 2 and MW-4 down gradient of Pond 2. Since MW-10 and MW-4 are both subject to ion exchange, and Cobalt is undetected in MW-10, but exceeds the groundwater protection standard in MW-4, Pond 2 must be the source of the Cobalt in the groundwater sampled from MW-4. The most likely sources of Cobalt at Pond 2 are the CCR components of the Poz-O-Pac and/or the "silty black gravel" which has an unknown composition.

CCR that has been mixed with other constituents for the purpose of structural fill is a beneficial reuse of CCR according to Section 3.135 of the Act and must be tested for leachability using a shake test or ASTM D 3987. The shake test results must not exceed Class I Groundwater Quality Standards (GWQS) in 35 Ill. Admin. Code 620.410.

In this case, the Illinois EPA maintains that the poz-o-pac must be tested for leachability of constituents listed in 35 Ill. Admin. Code 845.600(a)(1) and 620.410 to determine whether the poz-o-pac is contributing to the known exceedances of cobalt and detections of multiple other metals at Pond 2 downgradient wells as follows: arsenic, chromium, lead, lithium, and selenium. If the Petitioner, cannot demonstrate that the leaching potential of the CCR materials underlying the HDPE liner does not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600 then Pond 2 must be closed pursuant to Part 845 without an Adjusted Standard. If analytical results of the leach testing do not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600, then Pond 2 HDPE Liner integrity must be tested to prove competency as explained in paragraph c below and Attachment B.

b. Black silty gravel

In MWG's Response to the Illinois EPA's Recommendation, MWG did not provide soil total recoverable metals or metals leaching analytical data for the black silty gravel. At the hearing, Illinois EPA asked each of MWG's eight witnesses excluding Mr. Naglosky [plant manager], if they had any knowledge of the Poz-O-Pac or black silty gravel at Joliet 29 Pond 2 been analyzed for soil total metals or leachable materials. Each witness answered they did not know of any such analysis. Additionally, they provided no explanation of what economically, environmentally and geotechnically suitable materials other than fly ash could have been used as structural fill material mixtures at Pond 2. Furthermore, none of the MWG's witnesses could attest to the black silty gravel having been tested for its leaching properties or soil total metals properties. (TR. July 28, 2022, P. 33-34, 41, 49, 66, 94-95, 166-167; TR, July 29, 2022, P. 57).

In this case, the Illinois EPA maintains that the black silty gravel must be tested for leachability of constituents listed in 35 Ill. Admin. Code 845.600(a)(1) and 620.410 to determine whether the black silty gravel is contributing to the known exceedances of cobalt and detections of multiple other metals at Pond 2 downgradient wells as follows: arsenic, chromium, lead, lithium, and selenium. If the Petitioner, cannot demonstrate that the leaching potential of the black silty gravel underlying the HDPE liner or in the embankment of Pond 2 does not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600, then Pond 2 must be closed pursuant to Part 845 without an Adjusted Standard. If analytical results of the leach testing do not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600, then Pond 2 HDPE Liner integrity must be tested to prove competency as explained in paragraph c below and Attachment B.

c. HDPE Liner Integrity

In MWG's Response to the Illinois EPA's Recommendation and in testimony by their own witnesses MWG did not provide integrity testing results for the HDPE liner that MWG has requested to leave in place. Integrity testing, such as ASTM D 6747, ensures that seams and other wear and tear during operations and during the transition to the low volume wastewater pond they have indicated as the potential use, would provide analytical data demonstrating the liner is still sealed and impermeable for future uses.

In testimony, Mr. Naglusky, the plant manager, confirmed that heavy equipment has been used within Pond 2. TR. June 28, 2022, P.23. The Illinois EPA has viewed aerial photograph from 2019 showing that heavy equipment was used in Pond 2 to remove CCR. (Google Earth, accessed July 20, 2022, aerial photograph dated October 2019). Illinois EPA also reviewed aerial photographs from 2008 to 2021 and observed varying amounts of CCR and water were present over the years indicating that heavy equipment was used to remove the CCR on multiple occasions.

At the June 29, 2022 hearing, Mr. Dehlin, (TR. P. 59-60), confirmed that he is aware that ASTM D 6747 is a standard guide for selection of techniques for electrical leak location of leaks in geomembranes. Electrical leak detection techniques presented in ASTM D 6747 are non-destructive and therefore would not harm the integrity of the HDPE liner during testing. He also stated he believed that ASTM D 6747 was used when the liner was installed at Joliet 29 to ensure that the HDPE liner installation was completed sufficiently. TR, June 29, 2022, P. 59-60.

Mr. Naglosky testified that heavy machinery was used to remove the CCR "occasionally." The last time heavy machinery was used to remove material and clean Pond 2 was 2019. TR. June 28, 2022, P. 23-24.

In this case, the Illinois EPA maintains that if the Board allows the transition of Pond 2 to a low volume wastewater pond, there is a potential for damage to the HDPE liner from heavy equipment used over the course of several years to remove the CCR and cushion material between the HDPE liner and the CCR. Additionally, normal operations included heavy equipment used for CCR removal since it was replaced in 2013. (June 28th, TR. P. 23-24). Each time heavy equipment operates on top of the liner, there is the potential for liner damage to occur. Non-destructive integrity testing of the liner must be conducted to ensure competency of the liner before an adjusted standard is granted. 35 Ill. Admin. Code 845.770(a)(4) requires analytical testing to verify that a "competent geomembrane" is not contaminated by CCR. The Illinois EPA maintains that competency of a geomembrane must be proven using established integrity testing procedures which consist of ASTM D6747, or other ASTM design or construction related integrity tests, ASTM D or ASTM C applicable test methods. If the Petitioner can demonstrate that the liner is competent using an ASTM D or C related integrity test(s) such as ASTM D 6747, then the Board could approve the Adjusted Standard.

2. **Petitioner's adjusted standard petition should be denied because Petitioner failed to show adequate justification for the adjusted standard.**

The Board must consider economic reasonableness when adopting regulations. Section 27 of the Act provides: "The Board shall take into account…the technical feasibility and economic reasonableness of measuring or reducing the particular type of pollution." Economic reasonableness alone, however, is not an element in the required level of justification to obtain an adjusted standard as set forth in Section 28.1(c) of the Act.

The Petitioner states the following with respect to economic and environmental reasonableness [Pet. at e) p. 16 and 17]:

> "Compliance with the Illinois CCR rule for closure by removal by removing the liner as opposed to allowing reuse of it, entails significantly higher costs, including the total waste of a completely good, competent geosynthetic liner, with no added environmental benefits…The total cost for replacing the current liner with an almost identical new liner and removing the soil and poz-o-pac below is approximately $1,278,063."

The Illinois EPA maintains that the environmental impacts have not been adequately delineated by the Petitioner in that the Petitioner has not provided analytical data showing that there are no leachability issues with the black silty gravel or the poz-o-pac. The costs associated with removal of the CCR are explicitly only for removal and do not cover other containment or mitigation measures. On June 29, 2022, Mr. Dehlin testified to costs of removal of the liner. (TR, June 29, 2022, P. 35-38). However, MWG did not discuss in their Petition or at Hearing, the costs of placing a composite liner over the existing liner and encapsulating the black silty gravel and poz-o-pac to ensure that stormwater infiltration does not travel through any potentially "contaminated subsoils."

In this case, the Illinois EPA maintains that the potential environmental impacts must be characterized prior to determining whether the liner can be reused or if closure or other corrective action measures are needed to adequately mitigate impacts to human health and the environment. Until this is done, the adjusted standard should be denied.

3. **Petitioner's adjusted standard petition should be denied because analytical data gaps have not been resolved.**

The Illinois EPA maintains that the downgradient cobalt exceedances are from Pond 2. The Illinois

EPA Recommendation Exhibit O shows the cobalt above 35 Ill. Admin. Code 845.600 Groundwater Protection Standard (GWPS) at Pond 2 exclusively at MW-04 which is a downgradient well. Cobalt is detected but not exceeding the GWPS at MW-03 and MW-05, also downgradient wells. However, cobalt is not detected at MW-10, upgradient well at Pond 2, during any sample events between October 2015 to August 2021 reported in Recommendation Exhibit O, Joliet 29 Groundwater Data Summary. If the Petitioner, cannot demonstrate that the leaching potential of the poz-o-pac and black silty gravel underlying the HDPE liner or in the embankment of Pond 2 does not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600, then Pond 2 must be closed pursuant to Part 845 without an Adjusted Standard. If analytical results of the leach testing do not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600, then Pond 2 HDPE Liner integrity must be tested to prove competency.

4. Petitioner's adjusted standard petition should be denied because the adjusted standard does not meet the Federal closure by removal requirements.

The Adjusted Standard requested by the MWG is not consistent with the Federal closure by removal requirements.

Petitioner proposes the following language for its requested adjusted standard:

> "MWG may close by removing and decontaminating all areas affected by releases from Pond 2 at the Joliet 29 Station. CCR removal and decontamination of the Pond 2 is complete when the CCR in Pond 2 and any areas affected by releases from the CCR surface impoundment have been removed. MWG must conduct visual inspection and analytical testing to demonstrate that the geomembrane liner in Pond 2 is not contaminated with constituents listed in 35 Ill. Admin. Code 845.600(a)(1) and 620.410. MWG must submit the results to Illinois EPA."

Petitioner alleges that its proposed adjusted standard is consistent with federal law, stating that the applicable federal CCR rule and the United States Environmental Protection Agency's ("USEPA") Part B proposal both allow for decontamination of a liner and do not require removal. Pet. at 24, 25. Illinois

EPA maintains that Petitioner misrepresents the federal closure by removal requirements and that the proposed adjusted standard is not consistent with federal law.

First, the requested adjusted standard is not consistent with Part 257's closure by removal requirements, which explicitly require compliance with GWPS to complete closure by removal, as follows:

> "An owner or operator may elect to close a CCR unit by removing and decontaminating all areas affected by releases from the CCR unit. CCR removal and decontamination of the CCR unit are complete <u>when constituent concentrations throughout the CCR unit and any areas affected by releases from the CCR unit have been removed and groundwater monitoring concentrations do not exceed the groundwater protection standard established pursuant to 257.95(h) for constituents listed in Appendix IV to this part</u>."(Emphasis added).

As discussed previously, MWG has not proven that constituent concentrations throughout the CCR unit (e.g. liner, subsoils and berms) meet the GWPS because the poz-o-pac and the "black silty gravel" have not been analyzed for constituents listed in 35 Ill. Admin. Code 845.600(a)(1) and 620.410. Further, the federal closure by removal standard requires that groundwater monitoring concentrations not exceed GWPSs for Appendix IV constituents. Cobalt is an Appendix IV constituent and Cobalt at Pond 2 does exceed the GWPS in down gradient well MW-4, but is not detected in up gradient well MW-10. Therefore, the adjusted standard proposed by MWG does not meet the federal closure by removal standard.

Part 257 currently treats closure by removal and all associated corrective action as a single process, with closure not being considered complete until all corrective action, including groundwater remediation, has been completed. 40 CFR § 257.102(c). The 2015 Preamble indicates that USEPA intended for all CCR waste and the liner to be removed. USEPA states "once a facility has removed waste and the liner, the presumption is that the source of contamination has been removed as well." 85 Fed. Reg. at 12469. Furthermore, USEPA explains in the 2015 Preamble that part of attaining this performance standard is documentation that "any contaminants left in the subsoils (i.e. contaminated groundwater left in soils below the former landfill or impoundment) will not impact any environmental media including groundwater, surface water, or the atmosphere in excess of Agency-recommended limits or factors.... Once the facility has removed all the assessment monitoring constituents listed in Appendix IV down to background levels or MCLs, the groundwater is considered to be 'clean' and closure is complete." 80 Fed. Reg 21302, 21412 (Apr. 17, 2015). Clearly, USEPA envisioned a comprehensive removal and corrective action process for a CCR surface impoundment to be considered closed by removal.

In March 2020, USEPA proposed to divide closure by removal and corrective action requirements into two separate processes as part of a proposed rule known as "Part B." See proposed § 257.102(c). 85 Fed. Reg. 12456, 12477 (Mar. 3, 2020). USEPA cited new information posted to facility CCR websites, including the number of CCRSIs that are not lined with any type of composite liner system (such as Pond 2), as evidence that groundwater corrective action would be more complex than previously understood and should therefore be separated from the closure by removal process. 85 Fed. Reg. at 12469.[1] Proposed 40 CFR § 257.102(c) provides that closure by removal activities include "removing and decontaminating all CCR and CCR residues, containment system components such as the unit liner, contaminated subsoils, contaminated groundwater, and CCR unit structures and ancillary equipment." 85 Fed. Reg. at 12469, 12477. According to USEPA, for a complete demonstration that all CCR has been removed from the unit, "any containment system components such as a bottom liner, contaminated subsoils, and unit structures and equipment . . . would have to be removed prior to closure of the unit." If an owner or operator does not demonstrate compliance with GWPS, an owner or operator could qualify to separate corrective action

[1] "Available information indicates more than 70 percent of all CCR surface impoundments subject to the CCR regulations currently have neither type of composite liner system. Given the number of unlined CCR units, many of which have already reported exceedances of the groundwater protection standards, it is now evident that many CCR units have released CCR constituents into the surrounding soils and groundwater. This means that the closure activity is simply not a matter of removing CCR from the unit, but instead will likely require significant undertaking to remediate impacted soil and groundwater in order to achieve the current CCR removal and decontamination standards."

from closure if it has initiated corrective action, such that all components of the remedy are in place and operating as intended. See proposed 40 CFR 257.102(c)(2); 85 Fed. Reg. at 12469, 12477.

While the Part B proposal appears to require more than the current iteration of Part 257, USEPA states: "EPA is not proposing any substantive revisions to the current closure standard when closing by removal of CCR under 257.102(c)… EPA is, however, proposing to present the current closure standard in a slightly revised format…" for purposes of accommodating separation of groundwater corrective action from the rest of the requirements. 85 Fed. Reg. at 12469. USEPA's proposal to clarify the closure by removal requirements just reiterated its intention that the 2015 and current iteration of 40 CFR 257.102(c) requirements already include removal of unit liners and all contaminated CCR surface impoundment components and subsoils.

Illinois EPA proposed, and the Board adopted, the requirements in USEPA's Part B proposal, so that a CCR Surface Impoundment can receive a certification of closure by removal and therefore be relieved of fees under Section 22.59(j) of the Act, well before groundwater exceedances are resolved. Pet. Ex. 7, citing 85 Fed. Reg. 12456 (Mar. 3, 2020).

Part 845 must be as protective and comprehensive as Part 257. Illinois EPA maintains that Part 845 is as protective and comprehensive as Part 257, in part because: (1) Part 845 incorporates USEPA's proposed Part B revisions that explicitly require certification of removal of CCRSI components, including containment components such as liners and contaminated subsoils; (2) the reuse of a competent liner to supplement a composite liner allowed by subsection 845.770(a)(4) requires the owner or operator to provide analytical data for Agency review that will demonstrate that there are no contaminants left behind; and (3) compliance with GWPS must still be demonstrated for three consecutive years prior to terminating groundwater corrective action and groundwater monitoring.

MWG's proposed adjusted standard attempts to equate decontamination of a competent synthetic liner prior to retrofit of a CCR surface impoundment under 845.770(a) with decontaminating a synthetic liner and calling it closure by removal under 845.740(a). These two processes however are very different. When retrofitting a CCR surface impoundment, a composite liner compliant with 845.400 will be placed over the top of the cleaned liner, thereby preventing liquids in the impoundment from migrating through the impoundment components and subbase material. The reused liner simply adds an additional layer of protection. At the end of its useful life a retrofit CCR surface impoundment must still be either closed by removal under 845.740(a) or closed in place under 845.750. Allowing the Petitioner to certify as closed and decontaminated without removal of all the CCRSI components and contaminated subsoils circumvents these environmentally protective actions. Leaving the contaminated components in place, while not having a demonstration of compliance with GWPS, would not be as protective as Part 257.

As explained above, Illinois EPA disputes Petitioner's interpretation of 40 CFR § 257.102(c)'s closure by removal requirements, which USEPA has made clear includes removal of the CCR surface impoundment's liner, contaminated components and subsoils, and remediation of all GWPS exceedances. Even if Petitioner's interpretation of Part 257 allowing decontamination of the HDPE liner was accurate, its request to retain CCR material beneath the HDPE liner without demonstrating compliance with the GWPS would still be in contravention of the federal closure by removal requirements.

Therefore, Petitioner's adjusted standard petition should be denied because the adjusted standard does not meet the Federal closure by removal requirements.

WHEREFORE, for the reasons stated above, Illinois EPA respectfully recommends that the Board DENY Petitioner's petition for adjusted standard as Petitioner has not met its burden of proof to obtain an adjusted standard. In the event the Board decides to do anything other than DENY Petitioner's request for an adjusted standard over Illinois EPA's objection, Illinois EPA provides language for consideration that is attached as Attachment B.

Respectfully submitted,

Dated: September 13, 2022

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY,

Respondent,

BY: /s/Stefanie N. Diers
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Attachment A

Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering (2018); can be found in the included PDF

Attachment B

If the Board grants Petitioner's requested adjusted standard over Illinois EPA's objection, the Agency recommends that the Board only do so conditionally for a one-year period, during which Petitioner must conduct the ASTM D 3987-85 shake tests to evaluate the leaching potential of the poz-o-pac and black silty gravel underlying the HDPE liner within Pond 2's containment structures. Petitioner must collect a minimum of two samples in each of the four embankments at Pond 2 and three samples from the bottom of Pond 2 where the poz-o-pac was retained and utilized under the HDPE liner. The shake test samples in the embankments must be collected in a black silty gravel material no deeper than 515 feet above mean sea level ("AMSL") (or one foot below the bottom elevation of the liner at Pond 2). The shake test samples of the poz-o-pac from the bottom of Pond 2 must be crushed prior to conducting the shake test.

The shake test results must be compared to both 620.410 Groundwater Quality Standard (GWQS) (which is required to be environmentally suitable as CCB) and 845.600 (which identifies GWPS that specifically apply to CCR surface impoundments) and accompanied by the chain of custody and laboratory reports. Minimum reporting limits must be at or below the GWQS and GWPS. For constituents with standards in both Section 620.410 and Section 845.600, the minimum reporting limits for all laboratory analyses conducted by Petitioner must be at or below the GWPS in Section 845.600.

If Petitioner's shake test results demonstrate that the leaching potential of the CCR materials underlying the HDPE liner does not exceed the lowest standard specified in either Section 620.410 and Section 845.600:

a. Within the one-year interim adjusted standard period, MWG must conduct integrity testing of the liner seams and the HDPE liner to determine the competency of the liner. The liner competency must be certified by a licensed professional engineer, which must include certification that (1) the seams are intact and sealed, and (2) that the liner is not otherwise damaged.

b. If the liner is found to not be certifiably competent, then the Board should only allow MWG to retain the HDPE liner through a permanent adjusted standard if it installs a new composite liner meeting the design criteria of Section 845.400 overlying the old liner, where the old liner and its subbase will be considered part of the foundation of the new liner for purposes of Section 845.450(a)(1). A composite liner is appropriate for a low volume waste pond in this instance because the composite liner will isolate the liquids from the low volume waste from the poz-o-pac and black silty gravel left below the current liner, thus inhibiting further leaching.

If the Petitioner, cannot demonstrate that the leaching potential of the CCR materials underlying the HDPE liner does not exceed the lowest required constituent concentrations of Section of 620.410 and 845.600 then Pond 2 must be closed pursuant to Part 845 without an Adjusted Standard.

CERTIFICATE OF SERVICE

I, the undersigned, on affirmation certify the following:

That I have served the attached **NOTICE OF FILING** and **ILLINOIS EPA'S CLOSING BRIEF** by e-mail upon Kristen L. Gale at the e-mail address of kg@nijmanfranzetti.com, upon Susan Franzetti at the e-mail address of sf@nijmanfranzetti.com, Hearing Officer Brad Halloran at brad.halloran@illinois.gov and upon Don Brown at the e-mail address of Don.Brown@illinois.gov.

/s/ Stefanie N. Diers
September 13, 2022

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Article

Permeability and Leaching Properties of Recycled Concrete Aggregate as an Emerging Material in Civil Engineering

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Received: 26 October 2018; Accepted: 30 November 2018; Published: 26 December 2018

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Featured Application: Recycled concrete aggregate (RCA) is an emerging alternative material as a substitute for natural aggregate. The RCA blends test results in this paper has shown the appropriate coefficient of permeability for earth dam construction and for sub-base layers in road engineering. Moreover, the RCA is environmentally safe.

Abstract: In this article, a study of the threshold gradient and leaching properties for recycled material, namely, recycled concrete aggregate (RCA), was conducted. The RCA in this study is a material that comes from recycling concrete debris. A series of tests in permeameter apparatus in a constant head manner were conducted. The test method has been improved to eliminate common mistakes, which occur when the constant head method is used. During the following study, aggregates with gradations equal to 0–8, 0–16, and 0.05–16 mm were tested. The tests were conducted on gradients ranging from 0.2 to 0.83. This range of tested gradients led to the evaluation of the flux velocity and indicated non-Darcian flow. For engineering applications, the threshold gradients for three RCA blends were calculated using a statistical analysis. The average coefficient of permeability, k_{avg}, for linear flow was equal to 1.02×10^{-4}–1.89×10^{-4} m/s. In this paper, suffosion analysis was also conducted for the three blends in order to eliminate the possibility of particle movement. Moreover, for RCA blend 0–16 mm, leaching properties was examined. It was found that the concentration of chlorides, sulphates, and heavy metals in the water solution does not exceed the permissible standards. This paper ends with conclusions and proposals concerning the threshold gradients obtained from the statistical analysis, suffosion analysis, and flux velocity.

Keywords: permeability; recycled concrete aggregate; threshold gradient; constant head method; coefficient of permeability; leaching properties

1. Introduction

Increasing economic growth in Central Europe results in a growing waste problem. The development of recycling procedures, composting, and incineration facilities seem to prove the problem's existence. However, construction wastes constitute a large percentage (more than 50%) of solid waste stored in landfills [1]. Moreover, the failure to recycle such materials results in environmental disruption through disposing landfill, which is mostly unreasonable [2,3]. The industrial sector, associated with the construction of buildings and the demolition of existing structures, generates about 868.5 million tons of waste, which amounts to 34.7% of total waste production in the entire European Union [4]. At that time, 17.0 million tonnes of this waste were produced in Poland, which is 9.5% of the total [4]. To solve growing problem of construction and demolition waste, methods that would make it possible to reclaim construction materials are strongly desired. The life cycle of concrete, which ends with the demolition phase, is significant in the recycling process and should be handled with care because of potential reuse of the crushed concrete [3]. Therefore, knowledge about every possible property of demolished concrete is necessary and strongly demanded.

2. Literature Review

Aggregates are materials commonly used in civil engineering. For example, in the European Union and the EFTA countries in 2016–2017, around 30,000 tons of aggregates are used to create 1 km of new road [5]. These are mainly natural aggregates—such as crushed rocks, gravel, and sand—which constitute about 88% of the market demand [5]. Moreover, natural aggregates are the only material used in construction like earth dams, embankments, levees, or any others earthen construction. Designers and contractors are wary of using recycled aggregates, because the physical and mechanical properties are different from the natural aggregate behavior. The lack of detailed knowledge about recycled aggregates properties is another issue [6]. Despite this, in the last four years, the demand for recyclable aggregates increased from 5% to 8%, which is a significant increase on the scale of the European Union and EFTA (The European Free Trade Association) countries [5,6]. The largest number of recycled aggregates is produced in the UK, 52.3 million tonnes and in France 20.3 million tonnes compared to Poland, 5 million tonnes according to data for 2015, published in the bulletins of the UEPG—European Aggregates Association [5].

Among brick, glass, or soft materials—which are usually deposited at landfills—the most common waste is large size concrete debris. After the crushing process of this material is finished, concrete debris in a gradation curve from 0 mm to 63 mm are deposited and can be utilized as an aggregate or soil material. Commonly, in the literature, such porous media are called recycled concrete aggregate (RCA) and it is successfully used in road engineering. Therefore, a lot of geotechnical properties of RCA needed in road design are already known. For example, optimum moisture content for RCA with sandy gravel (saGr) gradation curve range from 8.35 to 11.74% [7,8]. Differences between optimum moisture content can occur due to various origins and different classes of concrete, from which the RCA was created. For example, RCA made of high-strength concrete with a lower water-to-cement ratio will present lower water absorption than RCA created from lower class concrete [6]. Another very important parameter in road engineering is California Bearing Ratio (CBR). Jiménez et al. [9] gives CBR values for RCA from 97 to 138%, Melbouci [10] gives one CBR value of 128%. According to Polish standards for roads WT-4 (Technical Specifications No. 4) [11], materials for the sub-base require a CBR value at least 60% and 80% for the base layer. Accordingly, RCA can be considered to be suitable for use in either sub-base or base layers. For correct prediction of road settlement resilient modulus is needed. Sas et al. [12] provides resilient modulus from 450 to 1710 kPa for numbers of loading cycles range from 10 to 50,000. They observed stiffness improvement with increase in numbers of loading cycles. Bozyurt et al. [13] presented empirical equations for resilient modulus based on particle shape, binder type and aggregate mineralogy of RCA. Arm (2001) in his cyclic triaxial tests show that RCA have the same resilient modulus as natural aggregate (NA), but over time laboratory and field tests showed an increase in stiffness for unbound layers with RCA. Arm [14] explained this fact by self-cementing properties of the unhydrated cement particle of RCA.

For other geotechnical applications, like aggregates for embankments or earth dams, mechanical parameters of RCA are needed. For RCA with gradation of saGr, O'Mahony [15] determined internal friction angle (φ) in direct shear test from 39.5 to 42°. Sas et al. [15] and Soból et al. [7] confirmed the test results presented by O'Mahony, but Sas et al. [16] from triaxial test estimated much higher value of φ equal to 53°. The cohesion phenomena which was reported during shear strength tests under RCA is still not fully explained. Usually aggregates do not behave cohesion.

But RCA has a very complicated structure and self-cementing properties which can lead to cohesion in non-cohesion soil. However, from a geotechnical point of view, self-cementation process is a phenomenon which improves mechanical properties of RCA [14]. Earth construction mentioned earlier often deals with dynamic loads like weaving or vibration caused by cars or trains. Small strain dynamic parameters like shear wave velocity, shear modulus, and damping ratio are needed to predict behavior of this structures subjected to seismic loads. Sas et al. [17] describe different procedures to obtained shear wave velocities from bender elements test. Gabryś et al. [18] use described methodology for RCA and got shear wave velocities from about 175 m/s for effective stress 45 kPa to about 300 m/s for effective stress 180 kPa. He and Senetakis [19] also obtained a similar value of shear wave velocity. For determination maximum shear modulus, shear modulus degradation curve, and minimal damping ratio of RCA, resonant column apparatus in cyclic torsional shear mode was employed in Gabryś et al. [20] article. They obtained maximum shear modulus from 62 MPa at 45 kPa effective stress to 220 MPa at 225 kPa effective stress and minimal damping ratio from 0.5 to about 3%. These reports also confirmed He and Senetakis [19]. Moreover, RCA has higher shear modulus than NA at the same effective stress, because of its sharpness and roughness which causes chocking of grains.

The coefficient of permeability k, is a key parameter characterizing seepage in soils, which is one of the most important in design earth dams or levees. However, also in road design, filtration layers need to be especially well characterized by the k value. When constructing a dam or levees, material for its body should has high permeability coefficient. Nevertheless, also in road engineering, even the subbase should have a high k value. However, such tests are often abandoned because of the low budget of a given investment. General tests are replaced by simpler methods, such as predicting the hydraulic conductivity on the basis of the porosity or grain size distribution [21]. As Chapuis [21] reported, hydraulic conductivity depends on the pore sizes and the way in which they are connected. However, well-graded natural soils are characterized by the presence of rounded grains, mostly of quartz origin with small roughness. In the case of slight clay particles content, the pores are still large and well connected. In contrast, RCA is characterized by high roughness grains with irregular shapes, which complicates the flow paths of water. Moreover, the internal pores are very often present in RCA, which greatly increases the specific surface [22]. The values of the void ratio, porosity, and therefore hydraulic conductivity in case of RCA are higher than a natural aggregate. The porosity of RCA, reported by Gómez-Soberón [23], is 14.86% when natural aggregates have 3% porosity. The high porosity was found to be caused by the presence of cement mortar. Deshpande and Hiller [22] report differences between the characterization of aggregates during a comparison between natural and recycled aggregates. Water absorption in this study, made with respect to American Society for Testing and Materials, Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate: ASTM C 127, gave different results for RCA when helium pycnometer and image analysis were conducted. RCA is a granular material that, as opposed to natural aggregates, is coated with patches of cement mortar remains. The remains of cement paste impact the results of the experiment, designed originally for natural aggregates (Tam et al. 2008). RCA's water absorptions after a 24-hour test increased from 5.72% to 8.28%. It is worth noting that 80% of the total water absorption was reached after the first 5 h [24]. This difference compared to natural aggregates may impact the RCA permeability properties.

The hydraulic conductivity of RCA was studied in works whose main purpose was to obtain the geotechnical properties, and extensive studies in this subject need to be performed. Arulrajah et al. [25] found the coefficient of permeability 3.3×10^{-8} m/s, which was similar to cohesive soils and materials used rather for dam and levee core than for dam body or filtration layer in road engineering. Nevertheless, a very low coefficient of permeability still was within the recommended value for a road subbase. Poon et al. [26] and Poon and Chan [27] reported the hydraulic conductivity of RCA in a range from 2.04×10^{-3} to 2.67×10^{-3} m/s. The differences between results [26,27] and [25] are very significant, which proves that more studies on this parameter should be carried out. The above-cited works did not mention the existence of non-Darcian flow. Nevertheless, the results of the experiments conducted by the abovementioned authors are in range of 2.04 $\times$ 10^{-3} to 3.3 $\times$ 10^{-8} m/s, which can indicate the existence of non-Darcian flow. Hansbo [28] showed that consolidation process in the cohesive soils leads to the formulation of a theoretical approach for dealing with this problem. The water flux in this study is proportional to a power function of the hydraulic gradient if the tested gradient is lower than a certain critical value. After this value, the gradient becomes linear for large gradient values. This behavior was explained by assuming that there is a certain hydraulic gradient in clayey soils that causes the binding energy to overcome the energy of mobile pore water. The threshold gradient is one of the parameters that constitute Hansbo's non-Darcian flow.

RCA formed on the basis of the different concrete will have unique chemical properties along with the different raw materials used in its production. As a consequence, it is not possible to identify all sources of heavy metals, but it is possible to identify materials that may be their source. Such materials include cement. The properties of heavy metals influencing their presence in the production process are their volatility. Non-volatile compounds—i.e., Ba, Be, Cr, As, Ni, V, Al, Ti, Ca, Fe, Mn, Cu, and Ag—leave the furnace as cement clinker components and are the source of metal content in the cement composition and thus also the source of heavy metals in RCA. In Table 1, the chemical composition of the basic constituents of the concrete from which the RCA is produced is presented. Presented data concerns only one kind of concrete and is not a general description for such material.

Table 1. Chemical composition of raw materials used in the production of concrete [29].

Parameter	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)	CaO (%)	MgO (%)	MnO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)
Cement	13.95	5.35	4.88	-	61.44	1.20	0.55	2.95	0.78	0.22	0.1717
Fly ash	50.40	27.31	4.79	1.50	7.29	1.49	0.06	0.46	1.52	0.28	1.06
Sand	26.66	1.76	1.00	0.09	30.85	6.89	0.04	0.01	0.24	0.22	0.00
Gravel	14.34	1.31	0.74	0.07	36.24	8.59	0.03	0.01	0.10	0.14	0.0

The high content of heavy metals and sulphates can lead to leaching of these compounds during a filtration process, which can cause significant environmental pollution. Therefore, it is necessary to analyze these RCA properties. One of the researchers that conduct studies of the leaching properties of RCA was Barbudo et al. [30]. They examined 17 mixtures of recycled aggregates with different contents of RCA, NA, ceramic, gypsum, bituminous, and other substances in laboratory. Barbudo et al. [30] proved that different mixtures with RCA do not exceeds the permitted standards of concentrations of heavy metals according to European Union (EU) Landfill Directive [31]. Similar study to [30] was performed by Engelsen et al. [32], but they conducted their tests in the field. They use RCA to build sub-base layers in three section on highway No. E6 located 20 km south from Oslo. Outgoing water from each sections of the highway was collected and tested for four years between 2006 and 2010. Concentration of heavy metals exceeds the limit only in the case of chrome. However, it could be connected with petroleum pollution from passing vehicles.

For successful application of RCA in road engineering and as an aggregate for earth dam, levees, and embankments, the permeability of RCA needs to be examined and analyzed. The aim of this study was to evaluate the use of aggregate from recycled concrete in road and embankments construction in terms of its permeability based on the designation of the coefficient of permeability and its variation, which was observed during this study. The main objective of the study was to determine the threshold gradient. Therefore, in the first instance, a series of analyses has been made in order to verify the correctness of the tests. The errors arising from the previous assumptions have also been estimated. Moreover, laboratory leaching tests of RCA was performed to determine potential environmental pollution.

3. Materials and Methods

3.1. Material

In this research, a tested demolished concrete was taken from a building demolition site by the skid-mounted impact crusher. The strength class properties of the construction concrete, made from Portland cement, were estimated to be from C16/20 to C30/35 based on the data obtained from building plans. The obtained material was later sieved into appropriate fractions with application of the [33]. The RCA was divided into three groups, namely, blends 1, 2, and 3. Each blend was composed from sieved fractions. The aggregates were 99% composed from broken cement concrete, the rest being glass and brick ($\Sigma(Rb, Rg, X) \leq 1\%$ m/m), in accordance with standard [34,35], and contain no asphalt or tar elements. A grain gradation curve was adopted in accordance with the Polish technical standard [11], which is a common technological guideline for road engineers, and placed between the upper and lower grain gradation limits. Besides, the created mixture is appropriate for earth structures like dams or embankments.

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In order to estimate the physical properties, a series of tests were conducted. The sieve analysis led to classifying the material as sandy gravel (saGr), in accordance with Eurocode 7 [36]. The test results are shown in Figure 1. This distribution of particles from 16 mm to 0 mm is in range of the standard for aggregates used as auxiliary subbase and improved subgrade in road engineering and in earth structures according to [11]. The coefficient of uniformity, C_U, indicates roasting granularity for all blends, but for blend 1, this value is significantly lower, mostly because of a low maximum grain diameter when compared to the other two blends. The coefficient of curvature, from 1.81 for blend 1, 2.16 for blend 3, and 5.56 for blend 2, indicates that this material is grading well. Moreover, the high value of C_U and C_C testify of the good compactibility [37] of the tested RCA, which is very important in earth construction. During this study, the void ratio for the 0–8 mm blend was approximately 0.386, for the blend 0–16 mm was approximately 0.543 and for the 0.05–16 mm blend was approximately 0.656.

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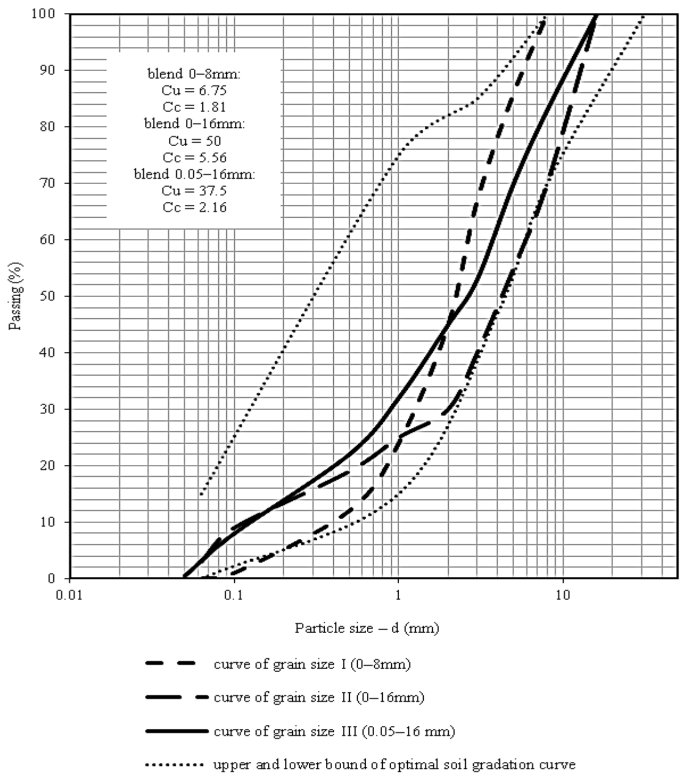

Figure 1. Grain size distribution curve of each blend.

Figure 1. Grain size distribution curve of each blend.

3.2. Permeability Test

There exist a variety of methods of permeability measurements using field methods that utilize BAT piezometers [38] and the falling head method with a flow pump [39–41]. However, a constant head method device was used in this study for estimating the basic characteristics of RCA because of its simplicity and invariable conditions of test. Moreover, the constant head method is one of the most reliable techniques of permeability measurements.

In this paper for permeability testing, laboratory equipment was used. A constant head device (called in this study as permeameter) is shown in Figure 2. Permeameter construction consists of inner and outer cylinders made form stainless steel (inner cylinder dimensions: height h = 0.17 m, diameter d = 0.205 m, outer cylinder dimensions: h = 0.27 m, d = 0.19 m), which are connected by a permeability mold also made from stainless steel, where the sample is placed. The permeability mold has a perforated bottom. After placing a sample, a perforated cover is installed on top. The permeability mold is fixed to the inner cylinder by four screws and an o-ring to make sure that no unexpected seepage of water from the outer cylinder occurs. The principle on which this device operates relies on communicating vessels, which allow the water to flow from the outer cylinder to the inner cylinder through the soil sample. The hydraulic gradient is simply set by the difference between the outer and inner water table heights. In practice, the inner water table is fixed, and the hydraulic gradient is inflicted by a changeable outer water table height. Tests were conducted when both the inner and outer water tables were in the fixed position. Measurements of the outflow water in time were repeated five times for each test point.

Tests were performed on three blends of grain, whose size was 0–8, 0–16, and 0.05–16 mm. The sample presented in Figure 1 were compacted in a permeability mold using Proctor's method. The energy of compaction was 0.59 J/cm3, and the mass of the compaction hammer was 2.5 kg. Compaction was conducted in three layers, where 16 strokes were performed for each layer. The sample volume was 6.34×10^{-4} m^3, with a diameter of 0.116 m and a height of 0.06 m. Proctor's method of compaction was used for the proper simulation of conditions that are present in the compacted layers of a road or embankment. Nevertheless, before compaction in a permeameter mold, a proper Proctor's study has been conducted. The RCA's maximal density and optimal moisture content were estimated as 1960 kg/m^3 and 8.0%, respectively.

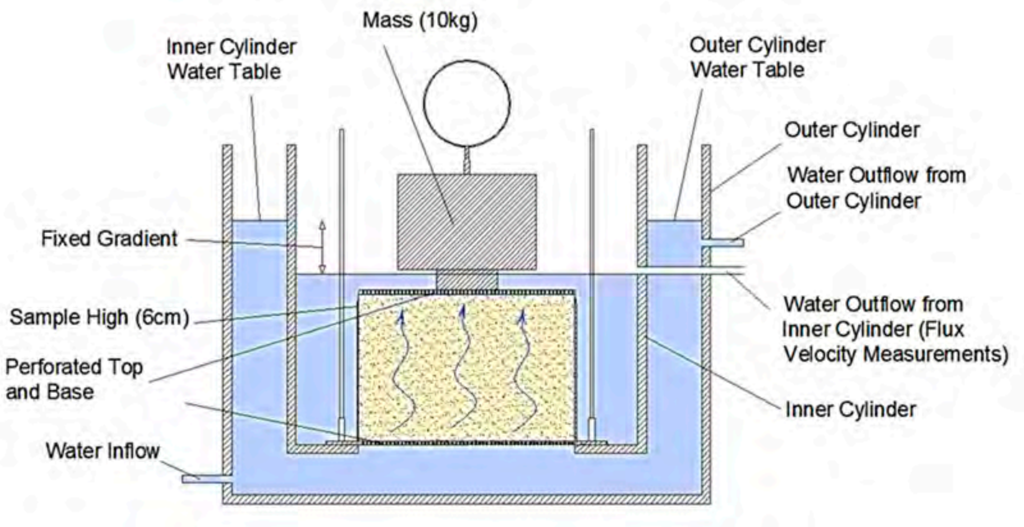

Figure 2. Permeameter scheme.

The procedure of the compaction and testing of the sample was upgraded several times before the main study in order to eliminate common mistakes, as reported by Chapuis [21].

(1) Compaction was performed with respect to the Proctor method in order to avoid crushing the grains, and this operation was performed in the permeability mold because of the risk of creating voids around the sample and the rigid wall. Compaction of samples was performed in the optimal moisture content, which was 8% [41]. This action was vital in order to simulate the performance of the subbase soil layer or compaction process in earthen construction.

(2) It is obvious that the permeability tests' saturation degree, S_r, has to be equal to 1. To solve this issue, after its installation on the permeameter, the sample was filled by aerated water at a constant rate of 0.25 mm/h of the water table, which, for a 6 cm sample, takes 24 h.

(3) Construction of the permeameter [41] made it possible to avoid hydraulic head loss because of the constant inner and outer water tables. The outflow was measured exactly next to the outflow pipe, which, during the tests, was never fully filled.

(4) Moreover, the movement of fine particles was controlled by checking the inside of the cylinder after the tests. Weight installed on the top of the perforated cover prevented the soil skeleton from movement due to the seepage of water.

(5) The pressure on the soil skeleton was equal to 10 kPa. The permeability coefficient was tested using the hydraulic gradients typical for water damming construction, which were 0.2, 0.3, 0.4, 0.5, 0.58, 0.67, 0.75, and 0.83, performed after 40 trials at each of the hydraulic gradients for each of the blends.

3.3. Chemical Analysis

Analysis of concentrations of chlorides, sulphates, and heavy metals in blend 1, 0–16 mm was studied. Samples for examines concentration of sulphates and chlorides was prepared according to Eurocode 7 standards (PN-EN 1744-1:1998) [42]. For determination of water-soluble sulphates and chlorides, methodology from Kiedryńska et al. [43] was employed. Namely, for chlorides concentration Mohr method and for sulphates concentration turbidimetric method were used. In the case of heavy metals concentrations, samples were prepared according to PN-Z-15009:1997 [44] standards. Atomic absorption spectrometry was use for identify concentrations of Co., Cd, Cu, Ni, Pb, and Zn in prepared specimens. Measurements was carried out on ASA ICE 3000 Series AA Spectrometer (produced by: Thermo Scientific, Waltham, MA, USA) device. Moreover, content of heavy metals in one kilogram of dry waste was calculated. Electrolytic conductivity and pH was also estimated. Every tests were repeated three times. During the all tests room temperature was fixed at 25 °C.

4. Results

4.1. Threshold Gradient and Suffosion

The permeability in soils obeys the Darcian law. The flux velocity v which is velocity the rate of flow of water is calculated as a product of coefficient of permeability k and hydraulic gradient i. The hydraulic gradient is a head difference inversely proportional to length. The studies under permeability of soils lead to find that not all types of soil behave Darcy's law. Figure 3 presents the relationships between the hydraulic gradient and the flow velocity in non–Darcian flow, proposed by Hansbo [28]. The RCA tests results have shown existence of non–Darcian flow. For engineering applications, non–Darcian flow is simplified to Darcian flow when the seepage of water starts from a certain gradient, which is called the threshold gradient. The existence of the threshold gradient comes from the assumption that when the gradient value is less than the threshold gradient, the flow rate may dramatically decrease, which follows non–Darcian flow [28].

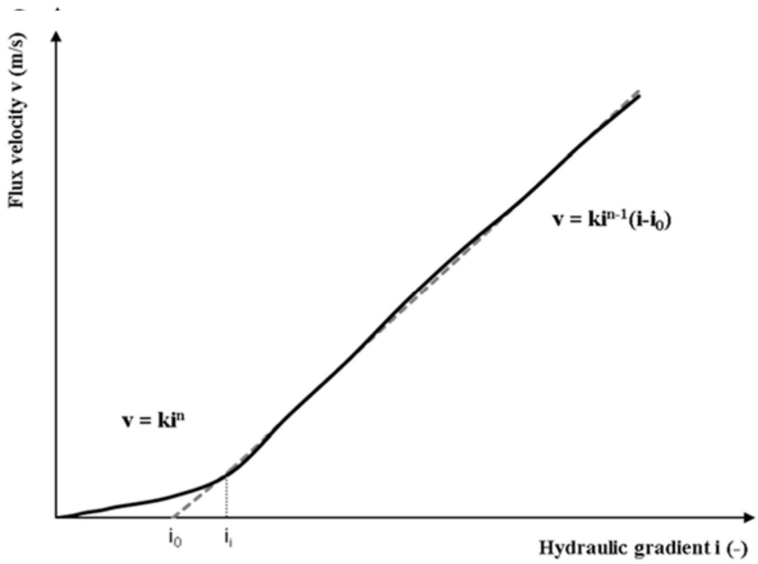

Figure 3. The relationship between the flux velocity and the hydraulic gradient in non-Darcian flow [28].

Figure 3. The relationship between the flux velocity and the hydraulic gradient in non-Darcian flow [28].

To exclude the possibility of unexpected suffosion during the tests, which could disrupt collected data, the occurrence of suffosion by Kenney and Lau [45–48] was analyzed. The results of the above analysis are presented in Figure 4. It has been concluded that suffosion occurs only in the blend whose particle size is 0.05–16 mm and only at a higher grain diameter, which is indicated by the occurrence of the crushing of the sample during the test. Nevertheless, the top perforated cover does not allow the grains to escape from the filtration hoop.

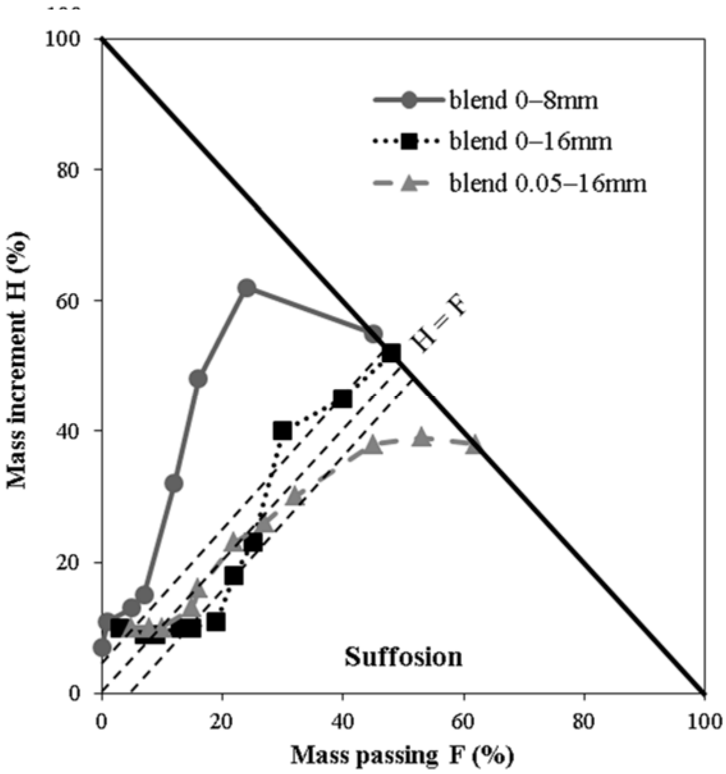

Figure 4. Results of suffosion analysis in respect to Kenney and Lau method [45] for the three blends of the RCA.

Figure 4. Results of suffosion analysis in respect to Kenney and Lau method [45] for the three blends of the RCA.

4.2. Results of the Permeability Tests

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Figure 5 presents the averaged results of the flux velocity for each gradient. In the graphs, two phases of seepage can be distinguished. The first pre-linear stage provides a low permeability in the blends with small gradients (i = 0.2–0.3). The second phase characterizes the linear flow in accordance with Darcy's law. For both phases of the flow, the R^2 value has been calculated. For the first phase of the pre-linear stage, the results were in the range of R^2 equal to 0.9853 to 0.9997. For the second phase, R^2 ranged from 0.9801 to 0.9966. The distribution of test results consists of the breakdown phase of the pre-linear and linear phases and is consistent with the theoretical recognition presented on Figure 3.

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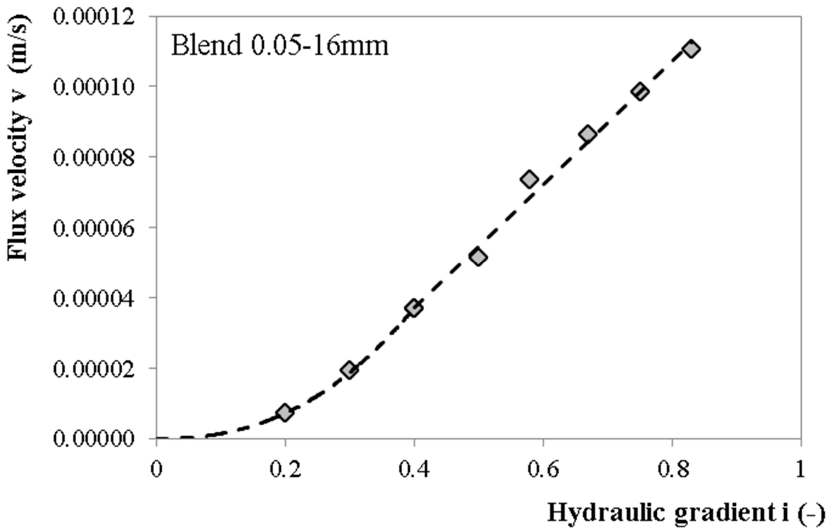
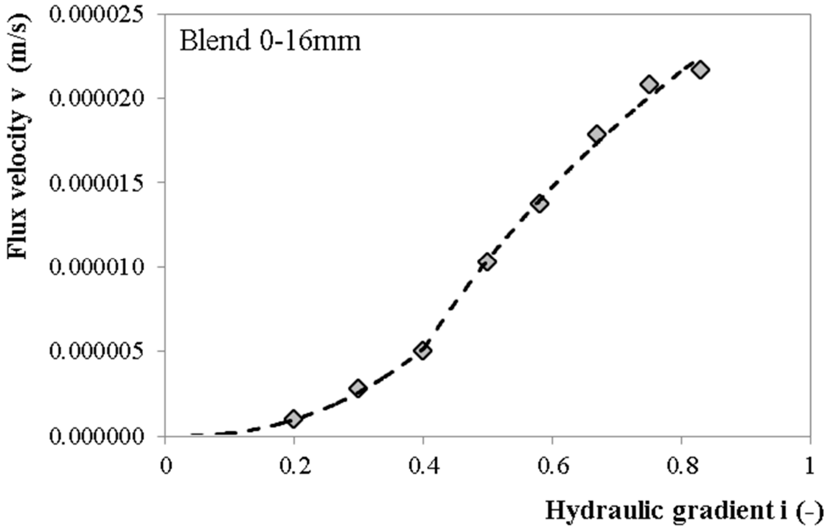


(**a**)



(**b**)

Figure 5. *Cont.*

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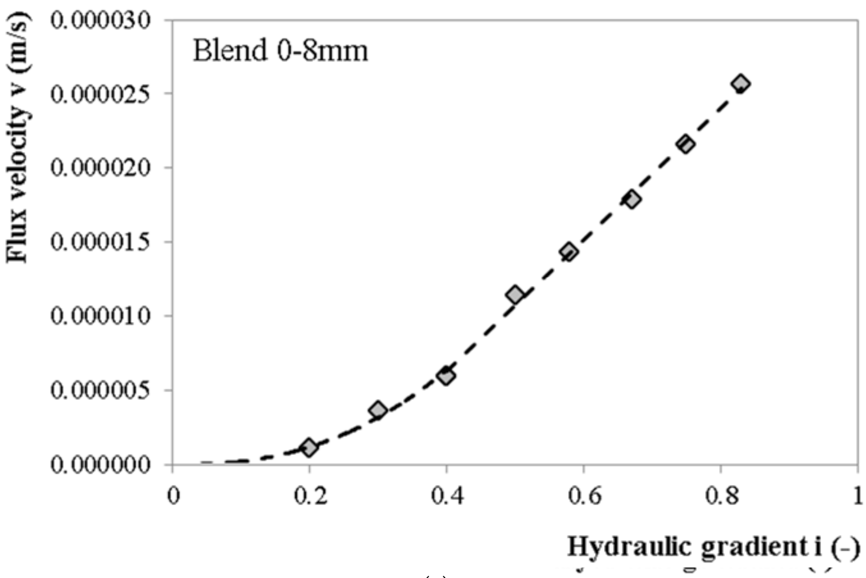


(c)

Figure 5. The relationship between the flux velocity and the hydraulic gradient for the blends: (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

The results of the tests shown in Figure 5 clearly indicate the existence of the threshold gradient. For low gradients (0.1–0.3), the flux velocity, *v*, is equal $v = k \cdot i^n$, where *k* is the coefficient of permeability, *i* is the gradient value and *n* is a parameter, which, in case of this test, was equal to 1.6 for the 0.05–16 mm blend. For the other two blends, *n* was equal 1.4.

4.3. Statistical Reliability of the Permeability Tests Results

In order to verify the normality, a Q–Q (quantile-quantile) plot graph and the Shapiro–Wilk test were used. The null hypothesis (H_0) for the Shapiro–Wilk test is that the distribution is normal for the result with $p \geq 0.05$. In the case of $p < 0.05$, the null hypothesis was rejected. The results for the Shapiro–Wilk test for all blends estimate the distribution for all blends as a normal distribution. Figure 6 shows the graphs for the Q–Q plot.

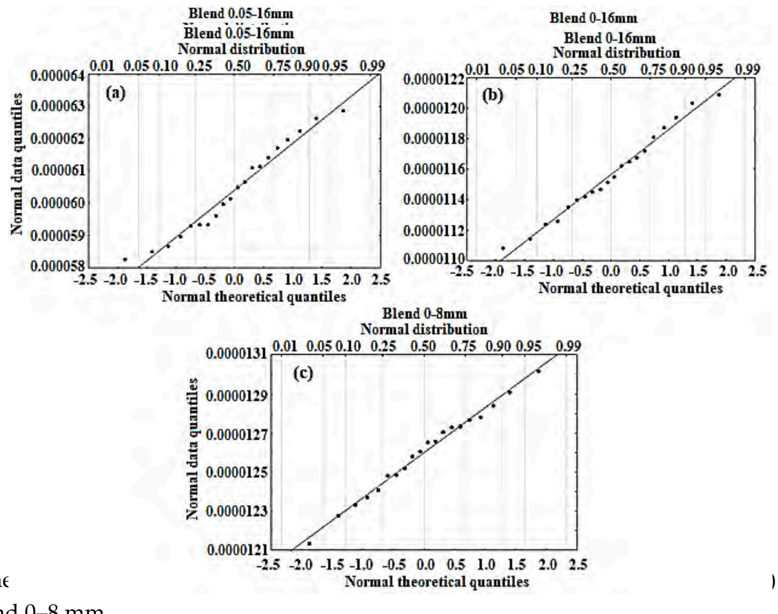


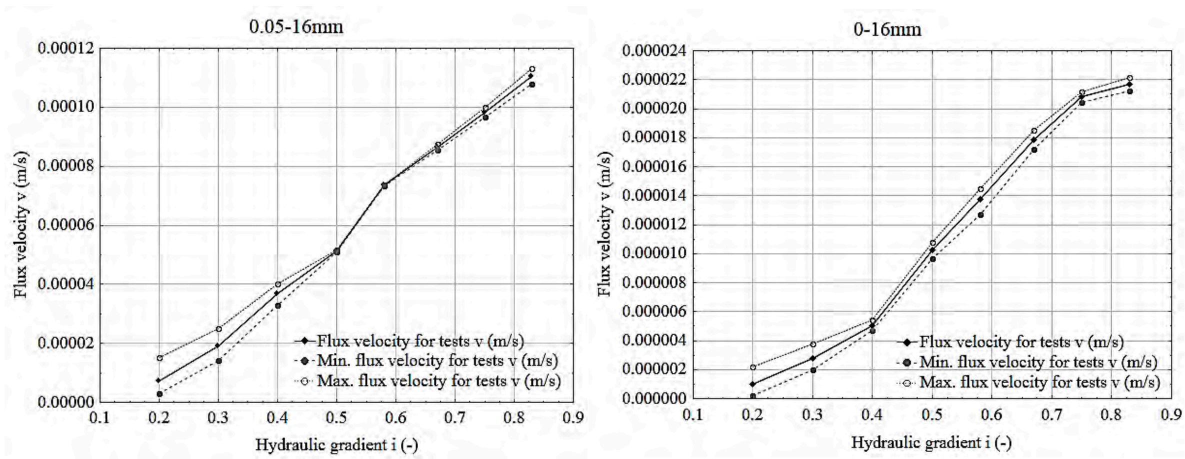
Figure 6. The Q–Q (quantile-quantile) plot graph for the blends: (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

For a better illustration of the nature and structure of the results and the accuracy of the tests performed, Table 2 summarizes the results of the analysis of errors for each of the tested gradients.

Table 2. Estimated errors of the flux velocity measurements for each of the gradients and blends.

Hydraulic Gradient i (–)	Standard Deviation	Absolute Error of Measurement (m/s)	Relative Error (m/s)	Percent of Error (%)
		Blend 0.5–16 mm		
0.2	3.4×10^{-6}	1.0×10^{-8}	1.1×10^{-4}	7.0×10^{-4}
0.3	3.5×10^{-6}	-4.0×10^{-8}	-2.3×10^{-4}	1.9×10^{-3}
0.4	2.4×10^{-6}	-1.0×10^{-8}	-4.0×10^{-4}	3.7×10^{-3}
0.5	1.4×10^{-7}	1.0×10^{-8}	1.0×10^{-4}	5.1×10^{-3}
0.58	1.5×10^{-7}	-1.0×10^{-8}	-2.0×10^{-4}	7.4×10^{-3}
0.67	5.8×10^{-7}	-1.0×10^{-8}	-2.0×10^{-4}	8.6×10^{-3}
0.75	1.2×10^{-6}	9.0×10^{-8}	9.0×10^{-4}	9.8×10^{-3}
0.83	1.8×10^{-6}	-1.2×10^{-7}	-1.0×10^{-3}	1.11×10^{-3}
		Blend 0–16 mm		
0.2	5.4×10^{-7}	3.0×10^{-8}	3.1×10^{-2}	1.0×10^{-4}
0.3	5.4×10^{-7}	3.0×10^{-8}	1.3×10^{-2}	3.0×10^{-4}
0.4	2.0×10^{-7}	1.0×10^{-8}	2.2×10^{-3}	5.0×10^{-4}
0.5	3.7×10^{-7}	-2.0×10^{-8}	-1.6×10^{-3}	1.0×10^{-3}
0.58	6.0×10^{-7}	3.0×10^{-8}	2.4×10^{-3}	1.4×10^{-3}
0.67	4.1×10^{-7}	3.0×10^{-8}	1.7×10^{-3}	1.8×10^{-3}
0.75	1.9×10^{-7}	0	1.0×10^{-4}	2.1×10^{-3}
0.83	2.7×10^{-7}	2.0×10^{-8}	9.0×10^{-4}	2.2×10^{-3}
		Blend 0–8 mm		
0.2	5.4×10^{-7}	4.0×10^{-8}	3.9×10^{-2}	1.0×10^{-4}
0.3	5.7×10^{-7}	4.0×10^{-8}	1.2×10^{-2}	4.0×10^{-4}
0.4	1.6×10^{-7}	1.0×10^{-8}	2.5×10^{-3}	6.0×10^{-4}
0.5	2.4×10^{-7}	2.0×10^{-8}	1.3×10^{-3}	1.1×10^{-3}
0.58	2.6×10^{-7}	-1.0×10^{-8}	-4.0×10^{-4}	1.4×10^{-3}
0.67	4.7×10^{-7}	0	2.0×10^{-4}	1.8×10^{-3}
0.75	2.9×10^{-7}	3.0×10^{-8}	1.3×10^{-3}	2.2×10^{-3}
0.83	5.0×10^{-7}	5.0×10^{-8}	2.1×10^{-3}	2.6×10^{-3}

The analysis of the test results in terms of the standard deviation and the interval between the highest and lowest result flux velocity for tests are also included (Figure 7). For the research conducted at low gradients of 0.2–0.3, the values for both the standard deviation and the interval were significantly higher. On this basis, we can conclude that the study at these gradients is unstable.



(a) (b)

Figure 7. *Cont.*

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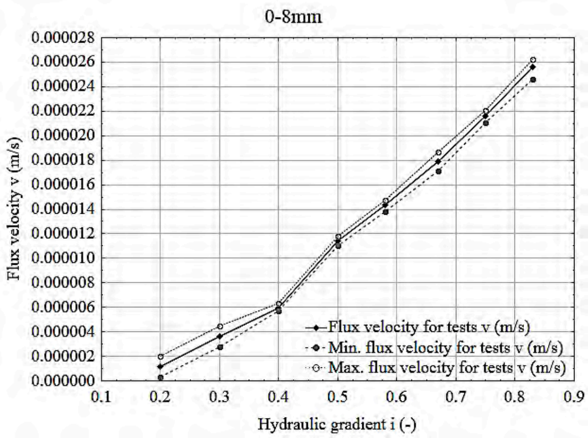


(**c**)

Figure 7. Prediction of the threshold gradient on the basis of the characteristic linear trend line with the minimal and maximal value flux velocities: (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

In order to determine the estimated value before calculating the flux velocity average all coefficients have been registered during the laboratory filtration process. The coefficient of permeability for all tests results was the mean, in accordance with which the average value of coefficient of permeability was calculated and presented in Table 3.

Next, the flux velocity was calculated using Darcy's Law, $v = k \cdot i$, where v is the flux velocity (m/s), k is the coefficient of permeability (m/s), and i is the hydraulic gradient, also included in Table 4. In the remainder of the paper, the results obtained on the basis of these calculations will have a specific name, flux velocity for k_{avg}.

In the next step, a graph of the relationship between the average of the flux velocity and the hydraulic gradient was constructed. The trend line was derived for these values, taking into account the confidence interval at 0.95 to define the threshold gradient. The test results on unstable gradients 0.2 and 0.3 were derived with an additional trend line, marked on Figure 8, representing an unstable flux velocity, in order to verify whether this will cause the cutting of the x-axis at 0 of the confidence interval for the used linear trend line equation. It can be concluded from Figure 8 that the points of intersection with the x-axis for the unstable flux velocity are within the confidence interval or at the border, designated for all tests at specified gradients for each blend.

Table 3. Calculation of the flux velocity on the basis of the mean coefficient of permeability.

i (-)	Blend 0.05–16 mm		Blend 0–16 mm		Blend 0–8 mm	
	k_{avg} (m/s)	v (m/s)	k_{avg} (m/s)	v (m/s)	k_{avg} (m/s)	v (m/s)
0.2	1.0×10^{-4}	2.0×10^{-5}	1.9×10^{-5}	3.8×10^{-6}	2.1×10^{-5}	4.2×10^{-6}
0.3		3.1×10^{-5}		5.7×10^{-6}		6.2×10^{-6}
0.4		4.1×10^{-5}		7.6×10^{-6}		8.3×10^{-6}
0.5		5.1×10^{-5}		9.5×10^{-6}		1.0×10^{-5}
0.58		5.9×10^{-5}		1.1×10^{-5}		1.2×10^{-5}
0.67		6.8×10^{-5}		1.3×10^{-5}		1.4×10^{-5}
0.75		7.6×10^{-5}		1.4×10^{-5}		1.6×10^{-5}
0.83		8.5×10^{-5}		1.6×10^{-5}		1.7×10^{-5}

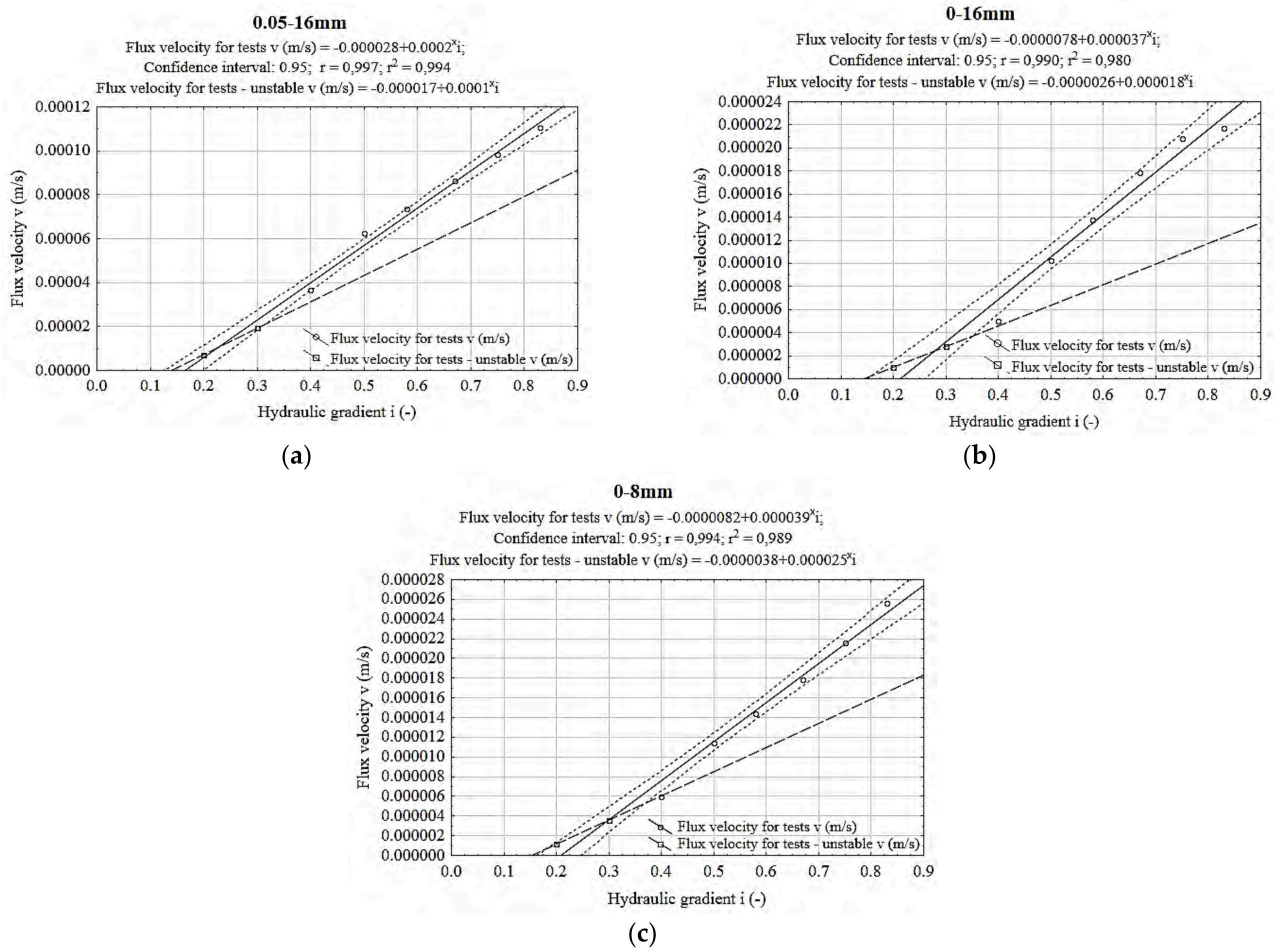
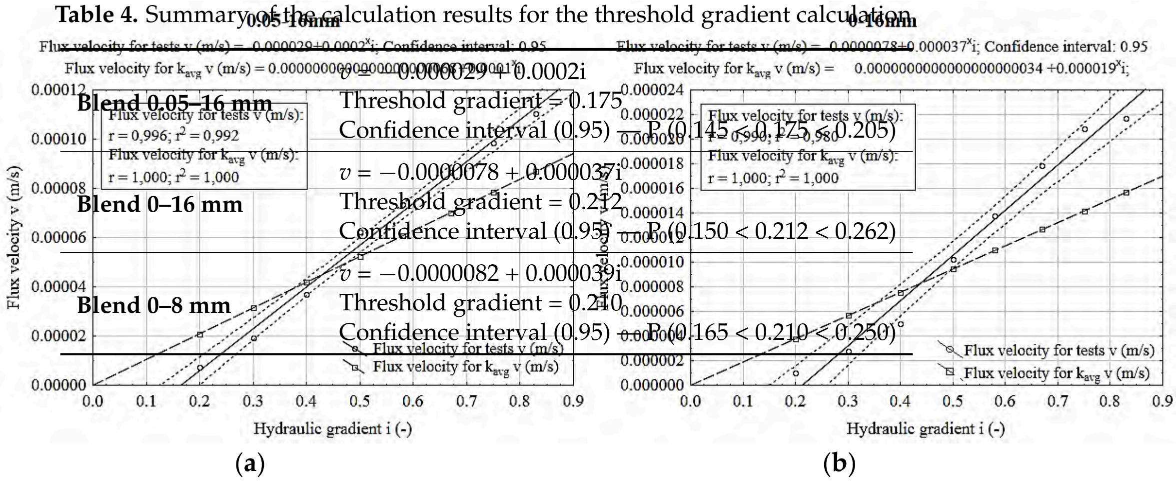


Figure 8. Relation between the flux velocity and the hydraulic gradient with unstable tests for the blends. (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

Figure 9 presents the two methods of determining the threshold gradient (i_0). The first is a simplified method based on k_{avg} and on the basis of the determination of the flux velocity described earlier. The calculations are shown in Table 4. The second method involves the determination linear trend line for the average of the test results for each gradient.

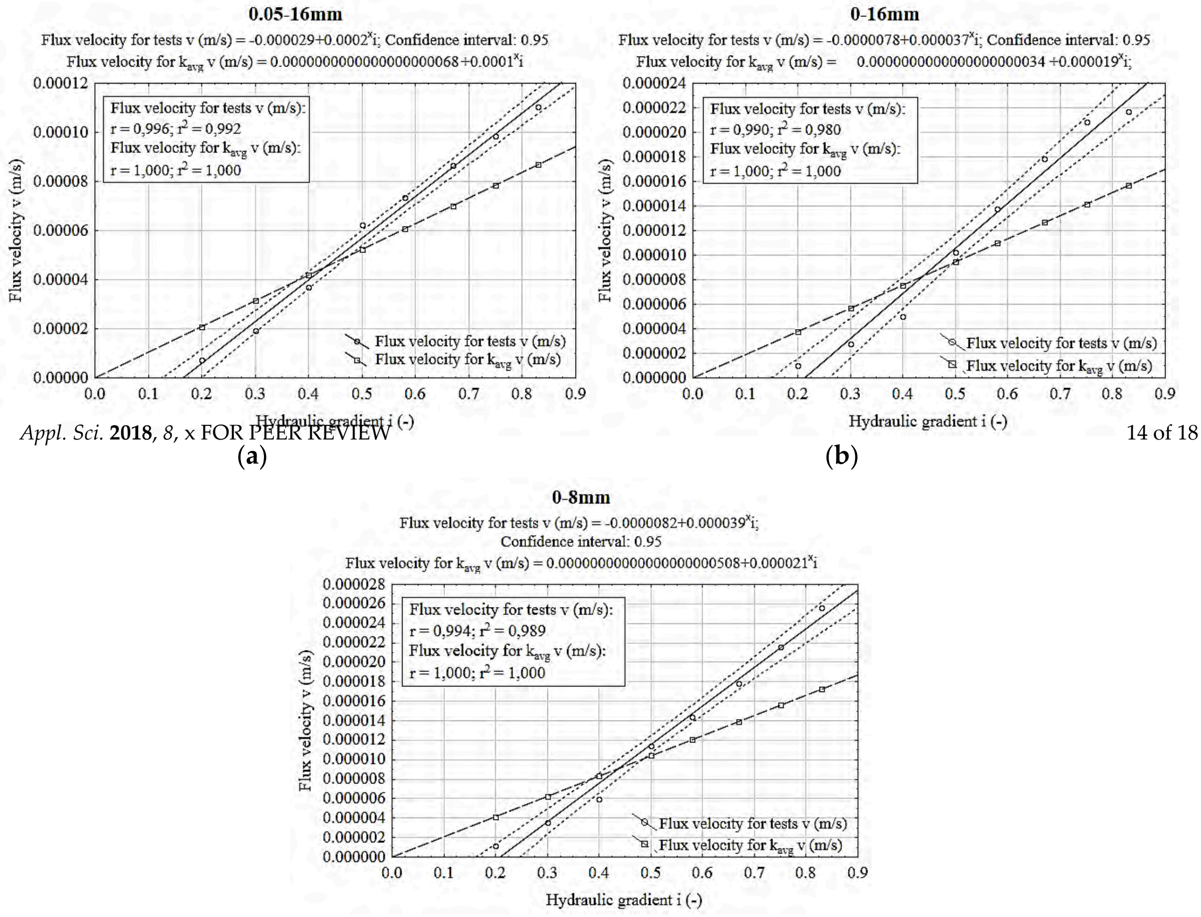
Table 4. Summary of the calculation results for the threshold gradient calculation.

Blend 0.05–16 mm	$v = -0.000029 + 0.0002i$ Threshold gradient = 0.175 Confidence interval (0.95) — P(0.145 < 0.175 < 0.205)
Blend 0–16 mm	$v = -0.0000078 + 0.000037i$ Threshold gradient = 0.212 Confidence interval (0.95) — P(0.150 < 0.212 < 0.262)
Blend 0–8 mm	$v = -0.0000082 + 0.000039i$ Threshold gradient = 0.210 Confidence interval (0.95) — P(0.165 < 0.210 < 0.250)



blends. (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

Figure 9 presents the two methods of determining the threshold gradient (i). The first is a simplified method based on k_{avg} and on the basis of the determination of the flux velocity described earlier. The calculations are shown in Table 4. The second method involves the determination linear trend line for the average of the test results for each gradient.



(**a**) (**b**) (**c**)

Figure 9. Prediction of the threshold gradient on the basis characteristic linear trend line for blend 0–8 mm. (**a**) blend 0.05–16 mm; (**b**) blend 0–16 mm; (**c**) blend 0–8 mm.

Table 4. Summary of the calculation results for the threshold gradient calculation

Blend 0.05–16 mm	$v = -0.000029 + 0.0002i$ Threshold gradient = 0.175 Confidence interval (0.95) — P (0.145 < 0.175 < 0.205)
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Blend 0–8 mm	$v = -0.0000082 + 0.000039i$ Threshold gradient = 0.210 Confidence interval (0.95) — P (0.165 < 0.210 < 0.250)

4.4. Chemical Analysis Tests Results

Results from conducted leaching tests of RCA are presented in Table 5. Every value from the Table 5 is the average from three performed tests. It can be seen that none of concentration values do not exceed acceptance criteria. However, concentration of cobalt and cadmium are well below the limit, which is 1.0 in case of cobalt and 0.05 in case of cadmium. Concentrations of copper and nickel are higher than metals mentioned earlier, but still about four times below the limits. Various values of concentration of these metals can be found in the literature. Galvin et al. [49] gives the values of copper and nickel equal to 0.28 and 1.75 mg/kg, but Del Rey et al. [50] provides 0.01 and 0.01 mg/kg. Lead and zinc have been not found in water extract made from RCA in this study, which is the confirmation of the Barbudo et al. [30] research. Concentration of sulphates is equal to 194.7 mg/L, which are the nearest to the acceptance criteria. Similar values of sulphate concentrations are reported in [31,50]. Chlorides concentration are on safe level of 14.05 mg/L in presented research. Galvin et al. [49] and Del Rey [50] reported higher chlorides concentration but still meet the norm. Moreover, Del Rey et al. [50] provided value of electrolytic conductivity 850 µS/cm, which is also higher than C = 501.5 µS/cm obtained in this study. However, both values indicated on little pollution of water extract made from RCA. Additionally, leaching of heavy metals are limited due to alkaline pH of RCA water solution. Moreover, small concentration of heavy metals are connected with concrete properties, which binds heavy metal compounds during the hardening process of concrete.

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Table 5. Leachate concentration from recycled concrete aggregate.

Element	Co. (mg/L)	Cd (mg/L)	Cu (mg/L)	Ni (mg/L)	Pb (mg/L)	Zn (mg/L)	Sulphates (mg/L)	Chlorides (mg/L)	C (µS/cm)	pH
Value	0.066	0.00067	0.121	0.127	n. d.	n. d.	194.7	14.05	501.5	7.91
Acceptance criteria *	1.0	0.05	0.5	0.5	0.5	2.0	500	1000	-	-

* Official Gazette of the Republic of Poland, Regulation of the Minister of the Environment of 18 November 2014 on the conditions to be met for the introduction of sewage into waters or to land and on substances particularly harmful to the aquatic environment.

5. Conclusions

In this paper, recycled concrete aggregates (RCA) were characterized using a permeameter with an upgraded constant head method in order to avoid the common errors encountered in such methods. The results were statistically analyzed to estimate the statistical tolerance. The suffosion and coefficient of permeability were also calculated. Moreover, leaching properties of RCA was analyzed in order to identify potential environmental threats connected with filtration process. The conclusions are summarized below:

1. RCA exhibit the non-Darcian flow of water with threshold gradient occurrence.
2. The value of the coefficient of permeability, k, changes with the void ratio, e, exponentially, and during further studies, empirical equations were determined.
3. The flow of water trough RCA is very sensitive, and in the case of one blend, turbulent flow was observed around a critical gradient, which, for this material, was 0.9.
4. RCA proved its good quality as a permeable material, which is characterized by a coefficient of permeability of 0.05–16, 0–16, and 0–8 mm, and the k values were 1.018×10^{-4}, 1.89×10^{-5}, and 2.08×10^{-5} m/s, respectively.
5. The threshold gradient was estimated in all blends, and statistical analysis shows the dependence of this phenomena on the fine particle content.
6. Fines also seem to be the reason behind the differences in the flux velocity between blends which do and do not contain them.
7. The threshold gradients for the tested blends of 0.05–16, 0–16, and 0–8 mm were 0.175, 0.212, and 0.210, respectively. Below theses gradients, for the tested blends the flux velocity may dramatically decrease, and water that stays in the RCA can degrade its mechanical parameters, including the bearing capacity, when road construction is considered or slope stability when earth dam or embankment construction is considered.
8. For road construction with standard gradients between 0.3 to 0.6, RCA has a constant value. Nevertheless, the threshold gradient needs to be taken into consideration when a large amount of fine particles is present in the material.
9. Obtained permeability coefficient for all examined blends are appropriate and meet requirements of aggregate for body construction of earth dams, levees, or embankments.
10. For earth dams or levees, a construction blend of 0.05–16 mm requires a reverse filter to avoid suffosion during filtration process.
11. Leaching of heavy metals during filtration process does not exceed the permitted limit. Although, the concentration of compounds having hexavalent chrome might exceed the limit. From a chemical point of view, RCA might be used as filtration layers in road, earth dam, or levee construction. Nevertheless, the concentration of other compounds harmful for life have to be checked before application.

The above results suggest the existence of possible permeability problems in roads or dams containing RCA layers. Nevertheless, such an occurrence concerns low gradients (below 0.3) and should be not an eliminative factor for application in above mentioned constructions.

Author Contributions: A.S. and W.S. conceived and designed the experiments; E.S. and A.G. performed the experiments; A.G., J.D., and E.S. analyzed the data and wrote the paper; W.S. and A.S. edited and audited the content.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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