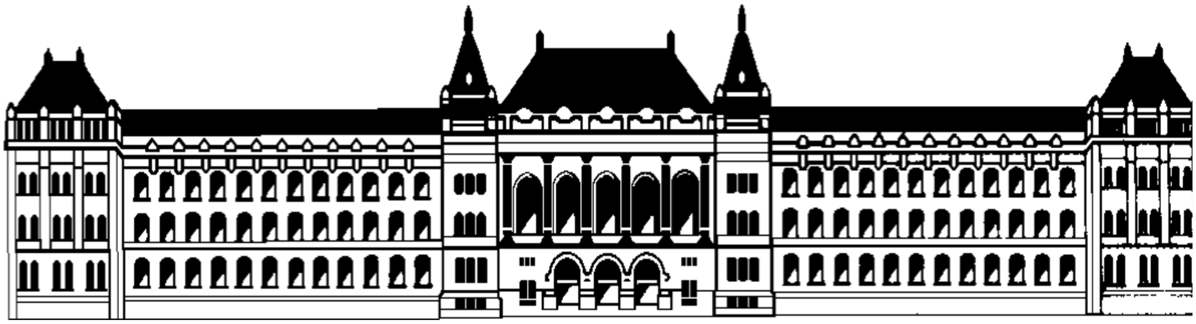

Budapest University of Technology and Economics
Department of Construction Materials and Technologies.

SCIENTIFIC STUDENT CONFERENCE (TDK)

INVESTIGATION OF DURABILITY PROPERTIES OF RECYCLED AGGREGATE CONCRETE WITH WASTE PERLITE POWDERS

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Contents

List of figures.

List of tables

Abbreviations

C&D- Construction and Demolition

SCM-Supplementary Cemtitious Materials

CM-Cementitious Materials

WPP- waste perlite powder

WPP-SZ- Waste Perlite Powder-Fine

WPP-C- Waste Perlite Powder-Coarse

OPC-Ordinary Portland cement

RAC-Recycled Aggregate Concrete

CA- Coarse Aggregate

FA-Fine Aggregate

RCA- Recycled Coarse Aggregate

RFA-Recycle-Fine aggregate

PD- packing density

ACI- The American Concrete Institute

RR- Replacement Ratio

SP- superplasticiser

Abstract

One of the most significant constraints for the wider application of recycled aggregate concrete is its higher porosity than natural aggregate concrete, leading to poor durability performance. Based on previous studies, particle packing has been identified as one of the most influencing factors in the porosity of concrete. In this study, the concrete mix design was based on optimizing particle packing for both aggregate and cementitious phases. Besides, including supplementary cementitious materials can reduce the pore sizes in cement stone, prohibiting durability deterioration mechanisms. The permeability of concrete substantially affects its freeze-thaw resistance. Cyclic freezing and thawing lead to significant concrete deterioration, particularly in the Central-European climate. Hence, the durability of the recycled aggregate concrete in this study

was investigated through the freeze–thaw resistance (frost-scaling) and water tightness tests as the essential durability measures.

1 Introduction

1.1 Alternative raw materials for concrete

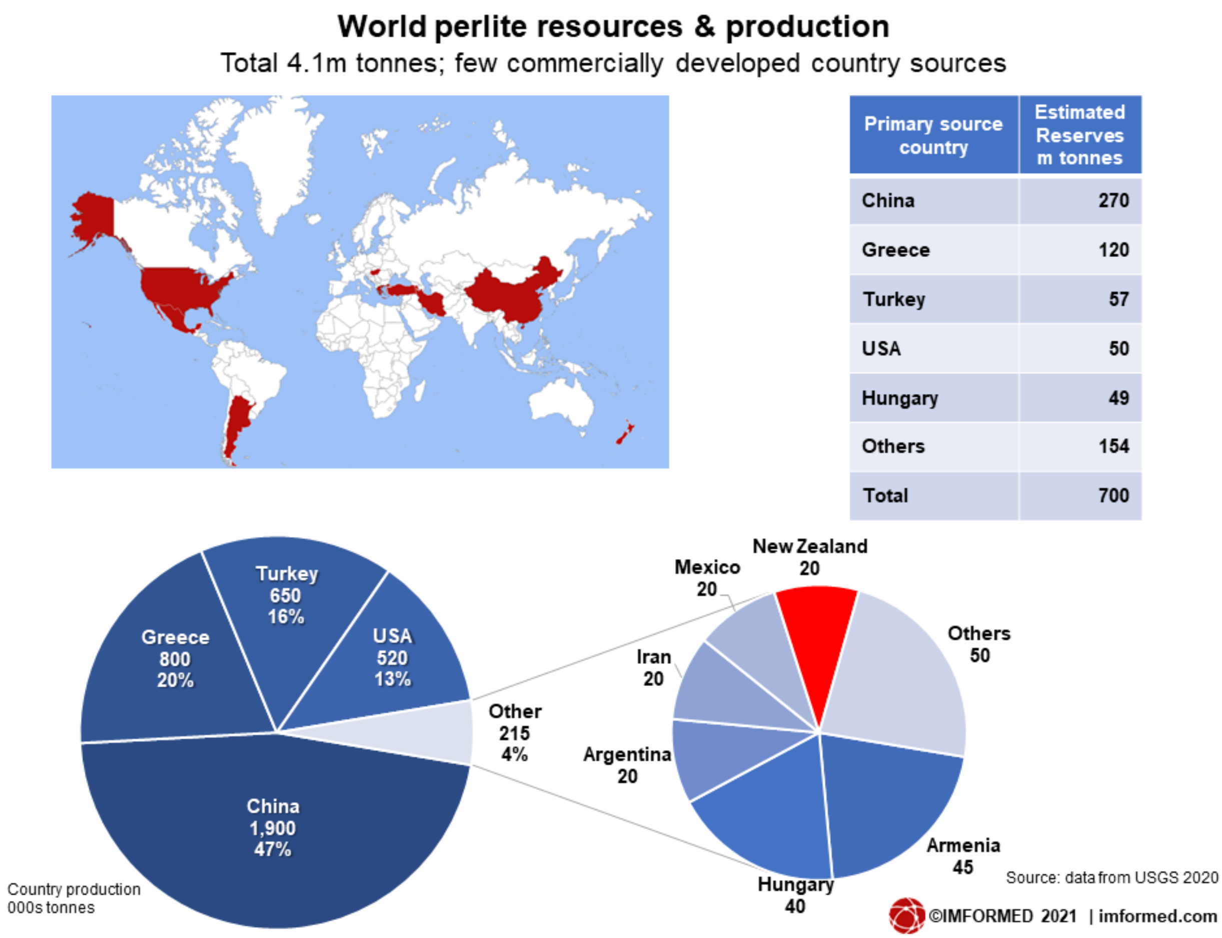
An estimated 20 billion tons of raw materials are used annually to make concrete, and a significant percentage of used building materials are squandered [1]. Around the world, the construction and demolition (C&D) industry consumes up to 40% of all extracted raw materials and produces roughly 35% of all waste [2]. The Environmental Protection Agency (EPA) defines C&D waste as waste from the construction, renovation, repair, and demolition of structures such as residential and commercial buildings, roads and bridges [3]. This waste includes a wide range of materials such as concrete, wood, metals, glass, plastics and gypsum, with the majority occupied by masonry and concrete rubble (67%) [2]. Due to the demand for cement, the construction sector is one of the leading industrial emitters of greenhouse gases, particularly carbon dioxide (CO_2). According to Rehan and Nehdi, the production of cement is an energy-intensive process that results in the emission of about 1 ton of CO_2 for every ton of ordinary Portland cement (OPC) produced [4]. Moreover, the destruction of existing and the construction of new buildings and other civil engineering structures are occurring at an alarming rate. This is partially because of human population increase and urbanization. Even further destruction occurs as a result of wars observed across most parts of the world i.e., Africa, Middle east and most recently Europe. Hence, the possible sustainable solutions in concrete industry should be based on reducing the amount of construction and demolition (C&D) waste and the amount of cement used.

The construction industry is the consumer of resources and one of the largest producers of waste in Europe, accounting for one-third of all waste and half of all resource extraction. The C&D waste generated at construction sites ought to be recycled and reused at a rate of 70% by the year 2020, according to the European Union's Waste Framework. Recycling of C&D waste generally across Europe, however, stands at only 28%, whereas some countries, such as the Netherlands, recycle up to 95% of their construction and demolition waste [5]. The EU even has short-term goals in place to enforce the recycling of between 50-90% of all construction and demolition waste within their jurisdiction [6].

Moreover, African data will be included in this study because of its market significance and the author's affiliation with the region. Data available indicates that Africa is rapidly urbanizing and developing its infrastructure, which is increasing the amount of waste generated during building and demolition. Studies have shown that C&D waste in Africa predominantly consists of materials such as concrete, brick, tile, wood, and glass. The C&D waste stream in South Africa alone is estimated at around 5-8 million tons [7]. Inferring from this data, we can suggest that there is a huge opportunity for growth in the recycling industry in Africa as it is for the rest of the world. South Africa as an example of an African country still has huge open areas and natural aggregate resources; thus, it is not unexpected that South Africa is trailing behind in terms of developing strategies to boost C&D waste recycling [8]

The performance of concrete materials containing recycled aggregate from C&D waste may replace natural materials in various civil engineering project sections. The use of these materials will result in significant changes in C&D waste reduction and natural resource conservation. Findings on the fundamental behaviors of recycled aggregate materials from C&D waste suggest that the performance of such concrete is satisfactory. However, it should be noted that in the same research, it was concluded that the use of recycled aggregate beyond a certain replacement ratio can cause serious structural damage [9].

Supplementary cementitious materials (SCM) are added to concrete mixtures for various reasons, including improving durability, decreasing permeability, aiding in pumpability and workability, mitigating alkali reactivity and improving the overall hardened properties of concrete through hydraulic or pozzolanic activity or both [10]. They are added to cement during the manufacturing process or used as a partial replacement for cement in concrete mixtures. In recent years, the usage of SCMs in the construction sector has grown in popularity, particularly in terms of producing concrete with lower carbon emission. Perlite is a natural amorphous material that is widely used in construction and industrial sectors. One of the largest producers in the world is Hungary [Perlite resources] and production [Figure 1]. Nevertheless, during the processing of raw perlite, a significant amount of waste material is generated in the form of perlite powder. The waste from perlite production constitutes approximately 5-10% of the original rock and has particles ranging from a few microns to about 0.5 mm [11]. This waste material presents difficulties for effective waste management and its perlite industry's environmental impact. Several research studies have been conducted to discover efficient methods for managing and using leftover perlite. One technique is to recycle leftover perlite powder in the construction industry. This not only helps mitigate waste disposal issues but also enhances the insulation properties and fire resistance of concrete [12]. Dacic et al. carried out an examination of mortar with WPPs and recycled concrete powder as an SCM by analyzing their hardened and fresh properties. The study discovered that WPP demonstrated higher reactivity, while the recycled concrete powder would act mainly as filler material [13] [14]. Hence, in this study, major ingredients of concrete will be replaced in specific amounts by alternative raw materials, namely recycled concrete coarse and fine aggregate, as well as WPP as SCM.



Perlite resources and production [Figure 1]

1.2 Durability of recycled aggregate concrete with waste perlite powder

The American Concrete Institute (ACI) defines durability as "the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service, all of which are serious phenomena that must be considered during the conceptual design stage; appropriate materials must be selected while keeping the target environment in mind in order to achieve good structural service life [15]. With the growing interest in alternative concrete mixtures, there has been a rise of interest in its durability properties, such as frost scaling and permeability. The frost resistance durability of concrete engineering structures in severe cold environments has become a research hotspot for many scholars [16]. Additionally, a number of authors have acknowledged that RAC exhibits unsatisfactory frost resistance in harsh climates. Hence, the research has also focused on predicting the optimum admixture or proportion that can improve frost resistance [17]. Permeability, on the other hand, is a crucial property of concrete, as it directly affects its durability and resistance to various factors, including freeze-thaw cycles [18]. Studies have shown that various factors, such as grain distribution of the coarse aggregate, the use of SCMs, and the treatment of recycled aggregate, can influence the water tightness of concrete. SCMs have been recognized to enhance the properties of RAC, including such as permeability and resistance to frost scaling. By previous investigations, it has been suggested that the use of WPP as SCM offers the potential to enhance the durability characteristics of concrete [19] [20]. Hence, combined utilization of WPP and recycled concrete aggregate might lead to beneficial durability properties.

Concrete's pore structure must be altered in order to increase durability, where more durable concrete usually has lower porosity, which is distributed more uniformly. [16] Frost resistance and permeability are two very important properties that affect the durability of concrete. Frost resistance of concrete is the ability of concrete to withstand freeze-thaw cycles without damage, while water tightness is the ability of concrete to allow water and other chemical agents to pass through it. The relation between the two was established by Zhang et al. [16]. They found that the smaller the water-binder ratio, the higher the strength and the better the corrosion, permeability and frost scaling resistance [16]. Concrete's capacity to resist frost can be impacted by permeability in a number of ways. Concrete can be harmed when water penetrates it because it may freeze and expand. The chance of freeze-thaw cycle damage might rise if the concrete is porous because more water is let in [18] [21]. Hence, low permeability might improve frost resistance, and high permeability decreases frost resistance. Bearing this in mind, investigating the frost resistance of concrete goes hand in hand with the investigation of its permeability [22]. Therefore, the primary subject of this paper is to investigate frost scaling and permeability of RAC with WPP as an SCM. The frost resistance can be improved by using air entraining agents however in this study we will deal with methods of reducing porosity of the concrete

2 Experimental research methodology

2.1 Materials

The properties of the aggregates (Figure 2.) used are shown in Table 1. In the case of cementitious materials, the OPC of the strength grade CEM I 42.5 was with density presented in Table 2. Moreover, as SCMs, two types of WPPs are utilized (Figure 3.) with the density as shown in Table 3.

a. CR *b. CN* *c. FR* *d. FN*

Aggregate types used [Figure 2]

Aggregate type	Oven-dried density [g/cm^3]	Water absorption [m%]	SSD density [g/cm^3]
Coarse recycled (CR)	2.39	3.6	2.48
Gravel (CN)	2.55	1.1	2.58
Fine recycled (FR)	2.16	8.2	2.34

Sand (FN)	2.59	0.7	2.61

Aggregates and their properties [Table1]

Waste perlite powders used [Figure 3]

Cementitious materials	**Density [g/cm^3]**
Ordinary Portland cement (OPC)	3.19
Waste perlite powder (WPP-SZ)	2.43
Waste perlite powder (WPP-C)	2.43

Cementitious materials and their density properties [Table 2]

Cementitious materials mix	RR by WPP-SZ(%)	RR BY WPP-(%)	Packing density
OPC	0	0	0.622
SZ2.5-C2.5	2.5	2.5	0.638
SZ5-C5	5	5	0.643

Replacement ratios and packing densities of cementitious materials *[Table 3]*

2.2 Mix design of concrete

Different volumetric ratios of the materials are used to come up with different mix designs. The denotations used during this experiment were used to explain what proportion/percentage of the ingredients is in the mix. The packing method was used to determine the optimal mix design. Both the aggregate phase and cement paste phase were optimized based on packing density. In this case, aggregate selected mixes have a packing density of 0.695, based on which cement phase quantity was determined (0.305). The water to binder ratio used is 0.4, while the superplasticizer amount varied to reach flow class F4 according to the standard EN 206. For this experiment, the

Viscocrete 5 Neu superplasticizer with a density of 1.1 g/cm^3 was used. In total 9 mixes were realized. The designation was based on the following coding RCx-Fy -CMq, where RCx-Fy part denotes aggregate mix with x volumetric replacement ratio of natural aggregate by coarse recycled (e.g., 30% replacement ratio- RC3) and y by fine recycled aggregate (e.g., 10% replacement ratio F1). On the other hand, CMq represents the used cementitious material mix where CMO, CM1 and CM2 represent mixes containing 100% OPC, 95% OPC with 2.5% of both WPP-SZ and WPP-C, 90% OPC with 5% of both WPPs. Finally, in Table 3, all examined mixes are presented. One mix sample in each of the three categories (CM0), which only has OPC as the cementitious material was used as a control sample mix.

RC4-F1-CM0	RC3-F1-CM0	RC2-F2-CM0
RC4N6-F1-CM1	RC3-F1-CM1	RC2-F2-CM1
RC4N6-F1-CM2	RC3-F1-CM2	RC2-F2-CM2

List of the mixes [Table 4]

2.3. Mixing procedure

The procedure begins by determining the water content of all the aggregate types. A sample size of all the aggregate types is weighed while it is still wet, dried in the oven and weighed gained. We use the following formulae:

$$\text{water content} = [(m_{wet\_}m_{dry}) \div m_{dry}] \times 100$$

The water amount is then adjusted according to the water required to reach the saturated surface dry condition of the aggregate. The mixing of the ingredients was then proceeded in five stages using the pan concrete mixer apparatus made of stainless-steel blades that rotate during mixing (Figure 4) as explained below:

<u>I stage</u>	<u>II stage</u>	<u>III stage</u>	<u>IV stage</u>	<u>V stage</u>
CR+CN (60s)	**FR+FN (60 s)**	**½ water (30s)**	**CM (30s)**	**½ water +SP (60s)**

Concrete mixer [Figure 4]

2.3 Preliminary study on consistency

After the mixing procedure has been conducted and all the five phases of mixing are exhausted, a flow table test is carried out. We add some water to the flow table while ensuring we don't have excess water settling on it. The cone is also wetted. We fill the cone halfway with concrete and use a rod tap 10 times the first layers, as shown in [Figure 5]. The cone is filled up with concrete completely and tapped 10 times again. The flow table is then lifted 40mm and then dropped 15 times, causing the concrete to flow. After this, the diameter of the flow of the concrete is measured in two orthogonal directions, and the average of the two is our test result. For this test, the desired diameter was between 49-55 cm, corresponding to the F4 flow class. If the result was less, a proportion of superplasticizer is added to the concrete and mixed again for a minute.

Flow table test [Figure 5]

2.4 Moulds

For both experiments conducted in this study, namely the water tightness test and frost scale resistance, the cube moulds were used with a dimension of 150×150×150 mm [Figure 6]. For each mix, 2 specimens were prepared for each type of experiment. Therefore, a total of 36 cubes were casted.

Filled cube mould [Figure 6]

2.5 Compaction

Once the moulds are prepared, a vibration table (Figure 7) is used to compact the concrete. The compaction procedure is as follows:

I. Fill the moulds in two approximately equal layers.
II. Vibrate each layer until the surface becomes relatively smooth in appearance. If the air bubbles stop appearing, stop the vibration immediately.
III. Place enough concrete in the top layer to entirely fill the mould when it is compacted; if the mould is not completely filled after the top layer has been partially crushed, add more concrete and finish compacting.
IV. Strike off and smooth the surface of the concrete.

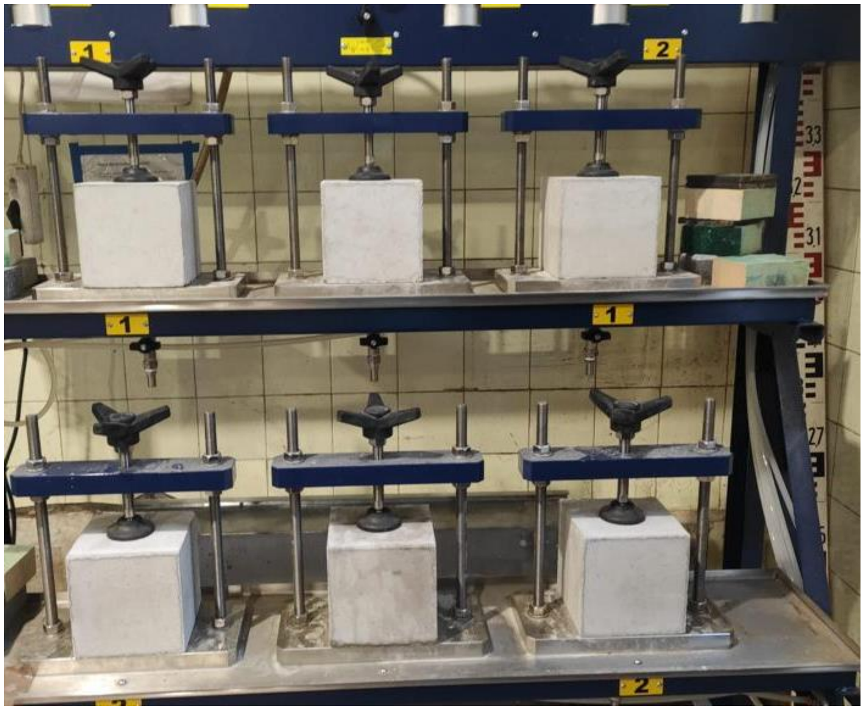
Vibro-table *[Figure7]*

2.6 Demoulding and curing

After (24 ± 2) hours, the concrete cubes and prisms are demoulded and submerged completely in a water bath at room temperature (20 ± 2) °C for 6 days. After that, the specimens are kept in a laboratory environment until the time of testing, which in this study was 28 days of age in the case of water tightness test and 31 days of age in the case of freeze-thaw resistance. Curing is essential for the development of concrete's strength, durability and resistance to cracking.

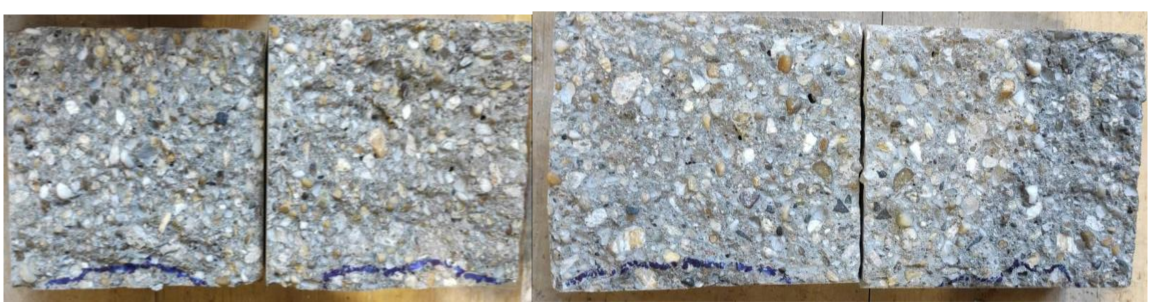
3. Water tightness test

For this experiment, a cube of 150×150×150 mm was used. The test started when the concrete was 28 days old, and the specimen was placed on the apparatus (Figure 8), where a water pressure of 500±50 kPa was applied from the surface of the specimen for 72±2 hours as prescribed in the standard EN 12390-8:2019 (E)) [23]. It is important to note that the troweled face of the specimen should not be used for the application of pressure.



Specimens placed in water tightness apparatus [Figure 8]

After the completion of the 72±2 hours long test, the specimen is split perpendicular to the same surface that the water pressure was being applied from. After a little while, the water penetration pattern is visible on the specimen, and the maximum seen point of the pattern is taken as our reading. However, it is important to note that in some cases, the water penetration pattern is not easy to see. Therefore, a think marker pen was used to highlight the pattern (Figure 9).



Highlighted water penetration marks on the specimen [Figure 9]

4. Test for freeze-thaw resistance

4.1 Preparation of the test specimen

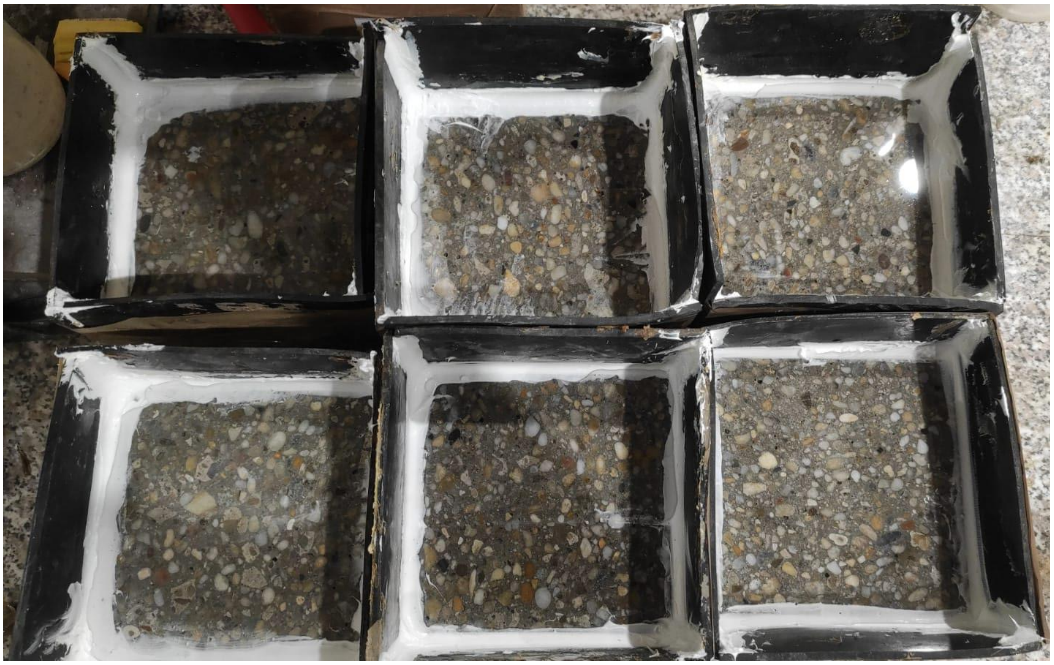
At 28 days, a (50 ± 2) mm thick specimen is sawn from each cube perpendicular to the top surface so that the saw cuts the surface we use for our test form the center, as shown below. The specimens have a dimension of 150×150×50 (±2mm) as a×b×c (Figure 10).

a B C

Cut specimen of the cube for freeze-thaw resistance test [Figure 10].

Immediately after cutting, the specimen is rinsed under in tap water, and then using a sponge, the excess water is wiped off. The cubes are measured again using a Vernier caliper (Figure 10) to ensure an accuracy of ± 0. 5mm. The following data was collected from the specimens.

The specimen is then covered by a rubber sheet of 3± 0.5 mm from all the surfaces except the test surface. Glue is applied on the specimen surface and the rubber sheet and then left out to dry for a while before the rubber sheet is bonded to the surface. A silicone rubber is used to join the inner side of the rubber sheet and the specimen to avoid leakage. However, it should be noted that at least 90% of the original test surface should still be visible after applying the silicone rubber. Water with a temperature of 20 ± 2 °C is poured on the top surface in a layer that is about 3 mm thick (Figure 10). The layer has to be kept at around 3 mm throughout this step, which lasts for (72± 2) hours at (20± 2) °as prescribed in the standard CEN/TS 12390-9:2006 [24].



Specimens covered with rubber sheets and 3mm of water added on top [Figure 11]

Afterwards, all the sides except the test surface of the specimen are thermally insulated with a 20±1mm thick polystyrene cellular plastic (with a density of (18±2) kg/m^3. The water left on the surface of the specimen is replaced with a sodium chloride solution with a concentration of 3m%. The top surface of the specimen is covered with a polythene sheet to prevent evaporation and held in place by a simple rubber band. The distance between the sheet and the surface of the freezing medium is at least 15mm. The final specimen looks as follows.

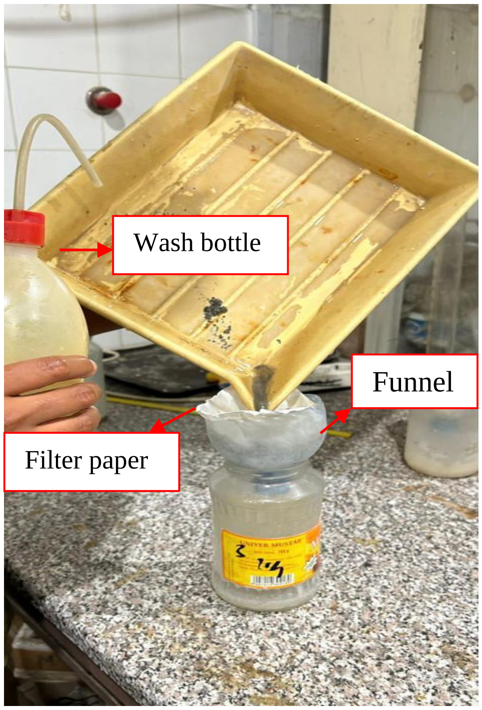
Specimen covered with a polythene sheet *[Figure 12]*

Once the specimens had been prepared, they were placed in a freezing chamber with temperature and time controlled by refrigerating and heating systems with a capacity such that the time-temperature curve could be monitored. It is important to note that in order to maintain the correct temperature cycle for all the specimens, it is necessary to have a good air circulation in the freezing chamber. The specimen is subjected to repeated freezing and thawing. During the test, the temperature in the freezing medium shall fall between -15°C to 25°C. The temperature shall exceed 0°C during each cycle for at least 7 h but not more than 9 h. The air temperature in the freezer shall never fall below –27°C.

After (7), (14), (28) cycles, the following procedure was carried out for each specimen during the thawed phase of the solution between 20 h to 24 h:

a) Collect any scaled material from the test surface using filter paper placed in a funnel into a collecting vessel (Figure 11). Use the wash bottle to rinse the surface, then scrape it gently to get rid of the scale.
b) Apply fresh freezing medium to the test surface. 67 ml are required for a 150 mm x 150 mm test area to have a thickness of about 3 mm.
c) Return the specimen to the freezer.
d) Wrap the residue collected carefully and place it on a brick in the oven to dry at a temperature of about 60°C.

The scaled material is weighted after it has dried, and the mass is recorded to the nearest 0.1g. The cumulative mass of the dried scaled material after a 28-day freeze-thaw cycle is determined and recorded as $\mathbf{m_{s,\,n}}$



Collection of the scaled material using a funnel, filter paper and wash bottle [Figure 13]

For the calculation of the total quantity of scaled material per unit area (**Sn)** after n (28±1) cycles, in kilograms per square meter, the following formula is used:

$$S_n = (m_{s,n}/A) * 10^3$$

Where

S_n - is the mass of scaled material related to the test surface after the n^{th} cycle.

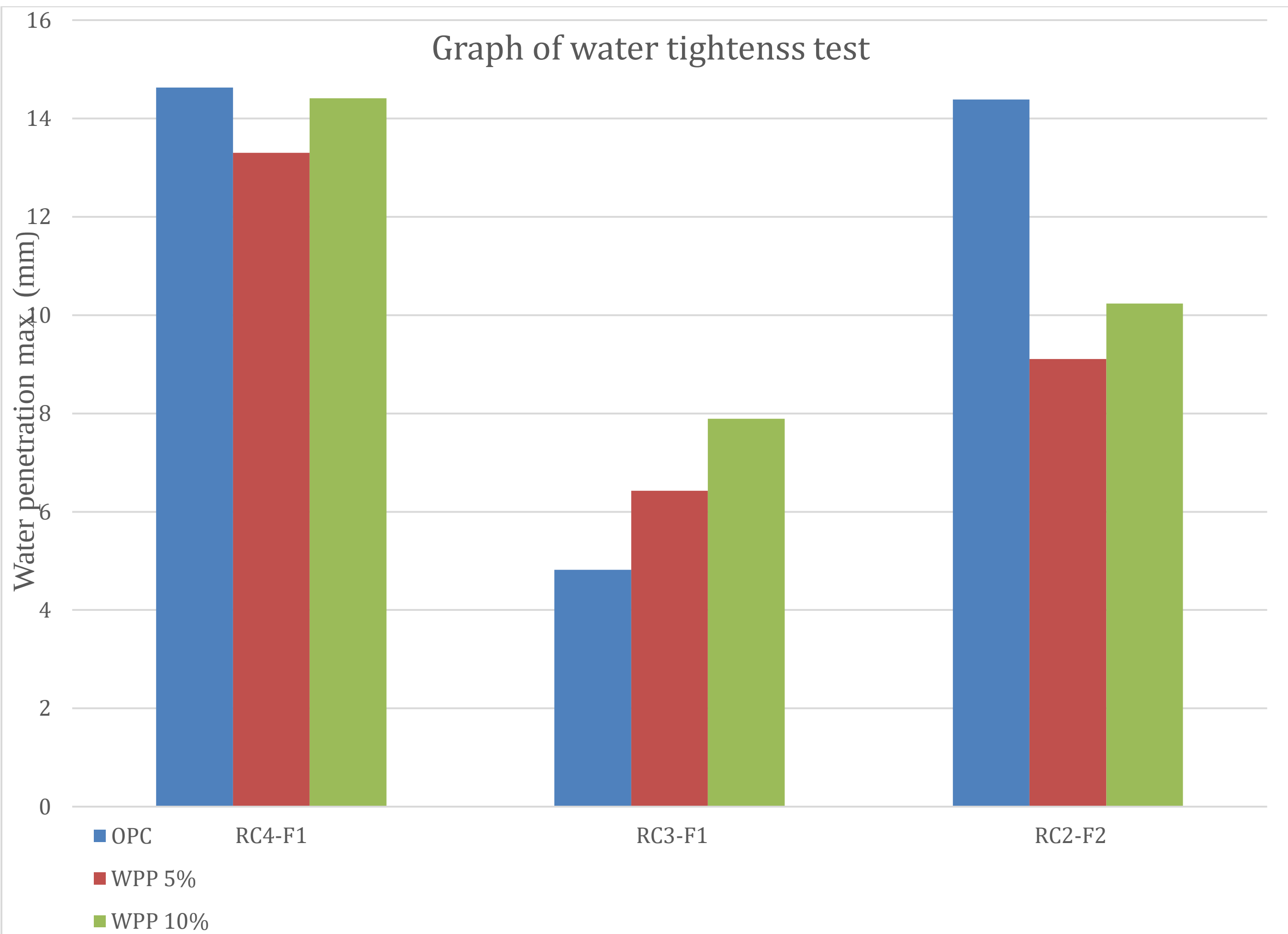
$m_{s,n}$ is the cumulative mass of dried scaled material after n freeze-thaw cycle.

A -is the total area of the test surface, calculated from the length measurements before the glue string is applied and rounded to the nearest 100 mm^2.

5. Test analysis and report

5.1. Test results for water tightness

After the test results were obtained, the data was analyzed on Microsoft excel and a graph was generated to help visualize the results. *[Figure14]*



Graph of water tightness against the material samples [Figure14].

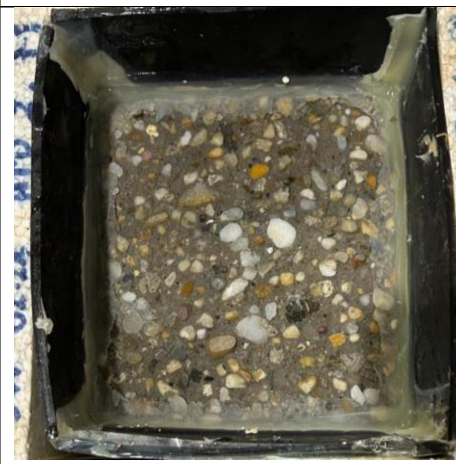
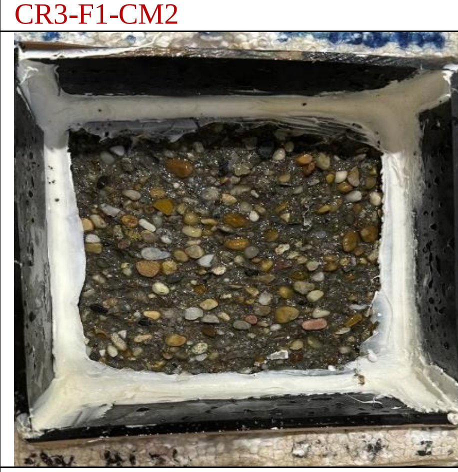
In *[Figure 14]*, it was observed that the different replacement ratios of the recycled aggregates (RC4-F1, RC3-F1, RC2-F2) together with the different ratios of the cementitious materials (OPC-100%, WPP-5%, WPP-10%) had different influence on the water tightness of the concrete sample. Generally, the group with the best water tightness can be observed to be RC3-F1, with both RC4-F1 and RC2-F2 exhibiting poor water tightness. In case of the aggregate mixes containing OPC only, RC3-F1 can be noted to be performing the best compared to both RC4-F1 and RC2-F2. Permeability stood at 4.82 mm,14.63 mm and 14.385mm respectively. Comparing both RC4-F1 and RC2-F2 to RC3-F1, we can note that there was an increase in permeability by 203.53% as we move from RC3-F1 to RC4-F1 and a 198.44% increase as we move from RC3-F1 to RC2-F2.

When the waste perlite powders are considered in all the mixes, there was an increased in permeability when the replacement ratio of the WPP is increased from 5% to 10% generally in all the mix categories. Permeability in RC4-F1 increased by 8.35%, RC3-F1 having 22.71% increase and RC2-F2 having a 12.41% increase. In RC4-F1 the mix with WPP 5% performed better than better (13.3 mm) than both mixes with OPC alone (14.63 mm) and WPP 10%(14.41 mm). In RC3-F1 the mix category with only OPC performed best having a permeability of 4.82mm while WPP5% and WPP 10% having 6.430 mm and 7.89 mm. It can be noted in RC3-F1 that addition and increasing the replacement ratio of WPP had a damaging effect on its ability to be water tight. In RC2-F2 mix category with WPP 5% outperformed mixes with OPC (14.385 mm) and WPP 10% (10.235 mm) by having a 9.105 mm permeability. In case of cementitious materials, the optimum mix could not be proposed due to variations mainly being led by aggregate mix hence, even substituting 10% in two of the mixes (RC4 and RC2 the results of permeability were better than for mix containing solely OPC). In this case, evaluation of other durability properties should be conducted to have more clear picture about the possible durability performance of investigated concretes.

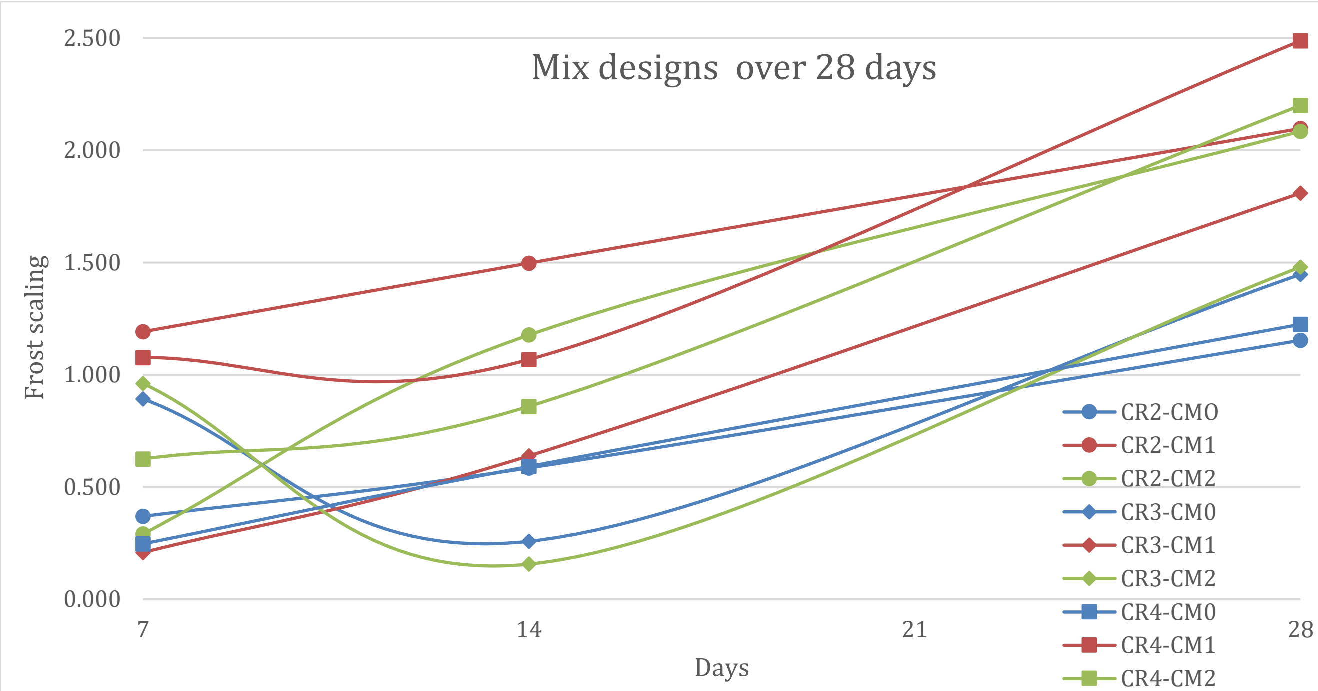
When the different aggregate mixes for the same type of cementitious material mix are considered, both amount of coarse and fine recycled aggregate seemed to be significantly influential. In mixes with 5% replacement ratio Permeability stood at 13.3 mm in RC4-F1, 6.43 mm in RC3-F1 and 9.105 mm in RC2-F2. Comparing RC4-F1 to RC3-F1, we established a 106.84% increase in permeability by only changing the replacement ratio of the coarse aggregate from 30% to 40%. Comparing RC2-F2(with 20% replacement ratio for coarse aggregate) side by side to RC3-F1 there was a 41.6% increase in permeability by just changing the replacement ratio of the coarse aggregate from 30% to 20%. In the categories of mixes with 10% replacement ratio of WPP, RC3-F1 is notably the best performing at 7.89 mm with RC4-F1 and RC2-F2 standing at 14.41 mm and 10.235 mm respectively. Increasing the replacement ration of the coarse aggregate from 30% in RC3-F1 to 40% in RC4-F1 and maintaining the same replacement ratio of WPP (10%) results in an 82.64% increase in permeability. Similarly decreasing the replacement ratio of the coarse aggregate from 30% in RC3-F1 to 20% in RC2-F2 lead to a 29.72% increase in permeability. The behavior of RC3-F1 against all the other mix designs suggest the existence of an ideal replacement ratio for coarse aggregate (30%). This has been suggested in a previous study by Ignjatović et al. that a replacement ratio between 20-30% does not have a detrimental effect on the compressive strength recycled aggregate, and if there is any strength loss, it is disregarded effectively [25]. Silva suggested a similar replacement ratio in his study [26]. Even though this study is not primarily focused on compressive strength, it is important to consider such findings. Additionally, the proportion replacement of 30% of RA in concrete mixtures has been proposed as the optimum by Gonzalez et al. and Jianzhuang et al. RAC under cycling loading was convenient for the structures in seismic areas[27] [28] The effect of recycled fine aggregate can be established from the behavior of RC2-F2 and how it performed in comparison to other mix categories with the same replacement ratio of the cementitious material. Comparing RC3-F1 and RC2-F2, it can be noted that in all the categories of mixes with OPC only, WPP5% and WPP10%, RC2-F2 performed poor despite the fact that these two mixes had the same total replacement ratio of recycled aggregate (40%).Therefore it can be deduced from this observation that a 10% replacement ratio for recycled fine aggregate is optimum while a 30% replacement ratio for coarse aggregate is optimum.

However, it is important to note that in RC4-F1 and RC2-F2, samples with WPP (both 5% replacement and 10% replacement) did better than samples with only OPC. This can be attributed to the fact that the packing density went from 0.638 (WPP 5%) to 0.643 (WPP 10%).A higher packing density translates to fewer voids therefore improving water tightness. Additionally, it could be possible that there has been pozzolanic reaction due to availability of some calcium phases from virgin concrete in RAC which provided possible pozzolanic activity even at the age of 28 days. The effect of pozzolanic activities on the concrete microstructure has been mentioned by Ramezanianpour et al. [20]. Similarly, Nehme et al. suggested that altering the pore structure of concrete could improve its water tightness by lowering the number of pores in concrete [19]. The influence of the pore structure on the durability of concrete has been investigated before [29], and it was concluded that altering the pore structure of concrete could improve its durability properties.

5.2. Test results for frost scaling

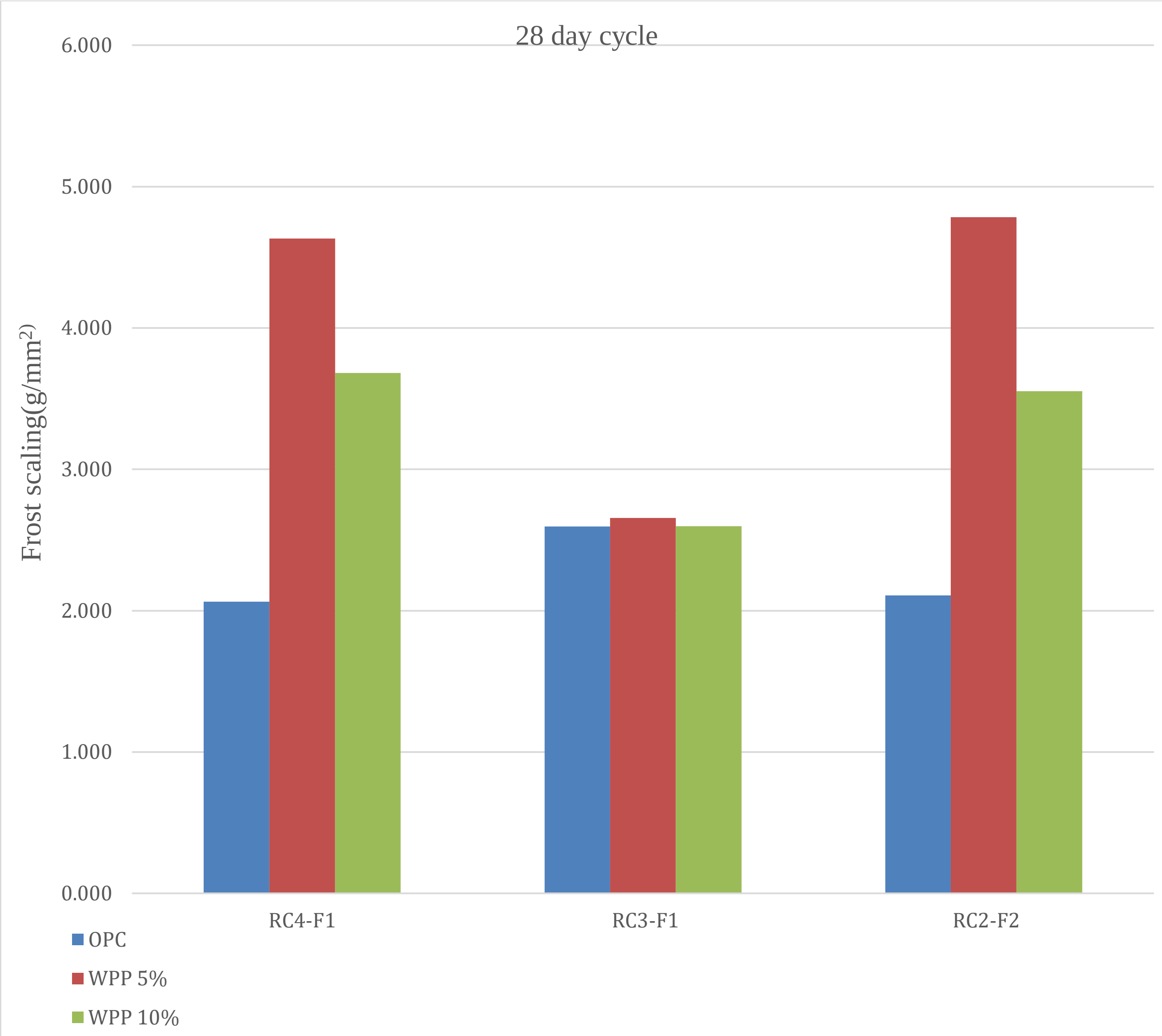
		
CR4-F1-CMO	CR4-F1-CM1	CR4-F1-CM2
		
CR3-F1-CMO	CR3-F1-CM1	CR3-F1-CM2
		
CR2-F2-CMO	CR2-F2-CM1	CR2-F2-CM2

Samples after 28 days' freeze-thaw cycle [Figure 15]



Graph of all the mix designs over the 28-day cycles [Figure 16]

From [Figure 16] it is observed that after 7 days of freeze and thaw cycle mix CR3-CM1 had the least frost scaling with CR2-CM1 having the worst performance. The two mixes had the same pattern of behavior at 7,14 and 28 days. However, CR4-CM1 had its lowest scaling on the 14th day similar to CR3-CMO and CR3-CM2. CR3-CM0 showed better freeze-thaw resistance after 14 days in comparison with all the mixes while CR2-CM1 again showing poor resistance.it can be noted from the trend that CR2-CM1 showed poor resistance at all stages of the test. Additionally, it can have noted that mix designs with the same replacement ratios of the cementitious material behaved more or less over course of the test. A more precise evaluation can be drawn from [Figure 17] below.



Graph after the 28-day freeze-thaw cycles [Figure 17]

The following observations can be made from *[Figure 18]*. RC3-F1 (30% replacement of coarse aggregate and 10% fine aggregate) has been established from this test to be the one with the best freeze-thaw resistance after 28 days cycle in comparison with the other mix designs (RC4 –F1 having 40 % replacement for coarse aggregate, 10% fine aggregate replacement and RC2-F2 having 20% replacement for coarse and 20% replacement for fine aggregate). The behavior of RC3-F1 has been noted before by researchers seeking to establish the optimum replacement ratio for recycled aggregate, as discussed previously in the analysis of the results for water tightness. [25] [26] [27] [28]. It can be observed that concrete samples with only OPC behaved almost the same way, even with different replacement ratios of the recycled aggregate. RC4-F1 stood at 2.063 g/mm^2, while RC3-F1 and RC2-F2 stood at 2.596 g/mm^2 and 2.108 g/mm^2, respectively, after 28 days.

When the waste perlite powders are considered in all the mixes with, WPP 5%, RC3-F1 was the best with 2.656 g/mm^2, RC4-F1 4.632 g/mm^2 and RC2-F2 having 4.785 g/mm^2. In mixes having WPP 10%, RC3-F1 (2.598 g/mm^2) was established to behaving better frost- scale resistance compared to RC4-F1 (3.682 g/mm^2) and RC2-F2 (3.553 g/mm^2). In RC4-F1, frost scaling went up from 2.063 g/mm^2 in the samples with OPC only to 4.632 g/mm^2. This is a 124.52% increase in frost scaling by just replacing 5% of OPC with WPP. A similar trend can be observed in RC2-F2, where frost scaling went up by 126.99%. These increase in the frost scale are more than two times the original. However, it is important to note that frost scaling went down in both RC4-F1 and RC2-F2 when the replacement ratio of WPP went from 5% to 10%. Frost scaling dropped by 20.51% in RC4-F1 and 25.75% in RC2-F2. This can be attributed to the fact that the packing density went from 0.638 (WPP 5%) to 0.643 (WPP 10%).

Packing density affects the ability of concrete to resist frost scaling in that when the packing density of cementitious materials in concrete is high, the spaces between particles are minimized, resulting in a denser and more compact structure. This dense structure reduces the ability of water to penetrate into the concrete, therefore decreasing the probability of frost damage. On the other hand, when the packing density is low, there are more voids and spaces within the concrete matrix. As a result, water is more easily able to infiltrate the concrete and freeze, leading to internal cracking and surface scaling during freeze-thaw cycles. WPP 10% has a WPP-SZ (fine) of 5% as opposed to WPP 5%, which has a WPP-SZ(fine) 2.5%. This has been proven to be crucial before by Kwan et al. in their study that supplementary cementitious material with a higher fineness is more effective because it would produce a broader range of particle size distribution [32]. From this observation it can be deduced that indeed WPP improves freeze-thaw resistance and a replacement ratio of 10% for WPP is better because of the improved packing density.

When the different aggregate mixes for the same type of cementitious material mix are considered, RC2-F2 and RC4-F1 has poor freeze-thaw resistance in comparison to RC3-F1 across all mixes with OPC, WPP5% and WPP10%. This can be explained by the interfacial transition zone (ITZ). ITZ plays a critical part in influencing the durability properties of recycled aggregate concrete. Recycled concrete is a more complex multiphase composite than normal concrete. Due to the porosity, surface roughness, aggregate particle distribution concrete, the micro hardness is somewhat discrete therefore making it susceptible to frost scaling [30]. The width and porosity of the ITZ can have a significant influence on the frost scaling of concrete. Generally, concretes with narrow transition zones tend to have low surface scaling and low internal damage, while concretes having a wider ITZ are more vulnerable to frost scaling due to their porosity increasing water penetration which is severe for the concrete in freeze thawing cycle [31]. RC4-F1 has a total replacement ratio of 50% (40% coarse and 10% fine); therefore, the effect of freeze-thaw was more severe in the concrete. In general, RAC has two ITZs, one originating from the parent concrete and one between RA and new cement paste phase, Hence, higher substitution by RA as the case in RC4-F1 would lead to higher presence of two ITZs leading to more vulnerable pore structure.

However, even increase in fine aggregate replacement due to typical higher amount of cement paste phase which is more porous could affect the final freeze-thaw resistance. Additionally, it should be noted that the influence of the higher replacement ratio of fine again in RC2-F2 has a significant effect on its frost scale resistance. Even though RC3-F1 and RC2-F2 have the same total replacement ratio (40%), only a 10 % increase in the replacement ratio of fine aggregate caused an increase from 2.598 g/mm^2 to 3.553 g/mm^2 (36.76% increase) in the samples with the same replacement ratio (WPP 10%).

6. Conclusions

The construction industry is a huge contributor to global pollution, and with the demand for construction materials seemingly increasing, it has become necessary to come up with more sustainable materials without compromising their quality. The goal of this research paper was to investigate how the use of waste perlite powder as a supplementary cementitious material would influence the durability properties (water tightness and frost scale resistance) of recycled aggregate concrete. The following conclusions can be drawn regarding durability properties investigated in this study:

1. Water film tightness

- The role of supplementary cementitious material in improving the durability properties of concrete by altering the pore structure of concrete has been established with RC4-F1 and RC2-F2, samples with WPP (both 5% replacement and 10% replacement) doing better than samples with only OPC. This behavior was attributed to increase in packing density from 0.638 (WPP 5%) to 0.643 (WPP 10%) and pozzolanic reaction due to availability of some calcium phases from virgin concrete in RAC which provided possible pozzolanic activity even at the age of 28 days.
- An optimum replacement ratio for coarse aggregate was established to be 30%. RC3-F1 (30% replacement for coarse aggregate and 10%replacement for fine aggregate) showed better water tightens across all replacement ratios of the cementitious materials (OPC 100%, WPP5% and WPP 10%) in comparison to RC2-F2 (20% coarse and 10% fine aggregate replacement) and RC4-F1 (40% coarse and 10% fine aggregate replacement)
- It was deduced from this observation that a 10% replacement ratio for recycled fine aggregate is optimum. This was properly established through the behavior RC2-F2 in comparison to RC3-F1. In all the categories of mixes with OPC only, WPP5% and WPP10%, RC2-F2 performed poor despite the fact that these two mixes had the same total replacement ratio of recycled aggregate (40%).

2. Freeze-thaw resistance

- Supplementary cementitious materials are indeed useful in improving the concrete's ability to resist frost scaling. Frost scaling dropped by 20.51% in RC4-F1 and 25.75% in RC2-F2 when the replacement ratio of WPP was increased from 5 % to 10 %. This can be attributed to the fact that the packing density went from 0.638 (WPP 5%) to 0.643 (WPP 10%). Packing density affects the ability of concrete to resist frost scaling in that when the packing density of cementitious materials in concrete is high, the spaces between particles are minimized, resulting in a denser and more compact structure. when
- Supplementary cementitious material with a higher fineness is more effective because it would produce a broader range of particle size distribution. This was established by the performance of WPP 10% which has WPP-SZ (fine) of 5% .in comparison to WPP 5%,

which has a WPP-SZ(fine) 2.5% and its influence on RC4-F1 and RC2-F2 where both mixes had a drop in frost scale when the replacement ratio of the WPP-SZ was increased.

- A 5% replacement ratio for WPP has proven to be very detrimental. In RC4-F1, frost scaling went up by a 124.52% and RC2-F2 frost scaling went up by 126.99% by just replacing 5% of OPC with WPP%. These increase in the frost scale are more than two times the original.

- A 30% replacement ratio for coarse aggregate was to be optimum. Concrete samples having 40 % replacement for coarse aggregate (RC4-F1) having the worst frost-scale resistance due to a large volume of recycled aggregate present in the concrete. Interfacial transition zone (ITZ) was established to be the explanation to this behavior. In general, RAC has two ITZs, one originating from the parent concrete and one between RA and new cement paste phase, Hence, higher substitution by RA as the case in RC4-F1 would lead to higher presence of two ITZs leading to more vulnerable pore structure.

- The influence of the higher replacement ratio of fine aggregate in RC2-F2 has a significant effect on its frost scale resistance. Even though RC3-F1 and RC2-F2 have the same total replacement ratio (40%), only a 10 % increase in the replacement ratio of fine aggregate caused an increase from 2.598 to 3.553 (36.76% increase) in the samples.

Based on the above findings, it is indeed possible to improve the water tightness and frost scale resistance of recycled aggregate concrete by utilization of suitable SCM mix considering packing density. For further studies frost scale resistance test until 56 days and other durability properties such as chloride ingress should be conducted. Additionally, including even 10% of WPP mix could lead to beneficial results in certain mixes giving promising milestone for further investigation and utilization of such concrete mixes.

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