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Production of green concrete using recycled waste aggregate and byproducts

Khalid Al-Gahtani, Ibrahim Alsulaihi, Mohamed Ali, Mohamed Marzouk,

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ABSTRACT

Purpose

This paper advocates utilizing recycled material in concrete production to support the sustainability benefits of using demolition and industrial refuse as a replacement for aggregates and cement in traditional concrete mixes. Crushed concrete from demolition sites served as a replacement for fine and coarse aggregate in some of the mixes at various replacements ratios. In addition, ground granulated blast furnace slag, metakaolin, silica fume, and fly ash each served as a cement replacement for certain proportions of the cement content in the tested mixes at various replacement proportions.

Design/methodology/approach

Compression strength tests, permeability, and thermal expansion tests were performed on various mixes to compare their performance to that of traditional mixes with natural aggregate, and with no cement replacement.

Findings

The compressive strength results indicated the suitability of using such demolition recycled materials as replacements in producing green concrete without significantly hindering its mechanical characteristics. In addition, the results indicated an enhancement in the mechanical characteristics of green concrete when replacing cement with pozzolanic industrial refuse and by-products.

Originality/value

This research investigates the sustainability benefits of using demolition and industrial refuse as a replacement for aggregates and reducing cement content in traditional concrete mixes.

Keywords: green concrete, recycled aggregate, cement reduction, sustainability.

INTRODUCTION

The construction sector is not only a massive consumer of nonrenewable resources, but also a massive producer of wastes (Bakhoum and Brown, 2011). Concrete is the leading construction material with an annual global production of about 3.8 billion cubic meters (i.e. ~1.5 tones/capita) (Garas, Allam and Bakhoum, 2014). Sustainability is concerned with the balanced and efficient consumption of resources, to achieve the social and economic needs of the society without much harm to the environment. Green concrete (GC) is a term that is used for environmentally friendly types of concrete mixes, in which a portion of the nonrenewable mix ingredients, is replaced by recycled ecofriendly wastes and byproducts (Nielsen, and Glavind 2007, Gursel et al. 2016). Accordingly, GC has the potential to meet both economic and environmental objectives of sustainable development. The production of GC incorporates replacement of any of the traditional ingredients, such as fine aggregates, coarse aggregates, and quantity of cement. Metakaolin, granulated blast furnace, fly ash, and silica fume are examples of industrial byproducts and wastes and can be used as pozzolanic materials to replace a portion of the GC cement mixture. Construction refuse such as recycled crushed concrete has the potential to replace a portion of coarse and fine aggregate content in the mixture of GC. The use of these industrial and construction refuse and byproducts reduce the environmental costs of their traditional disposal, and also reduce the production costs of new raw materials that are used in traditional concrete mixes. The main objective of this research is to investigate the characteristics of concrete when considering recycling demolition and industrial refuse as a substitute for aggregates while reducing the cement content in traditional concrete mixes. The following section investigates efforts in literature directed towards the reuse of construction debris and byproducts in the production of GC mixes.

LITERATURE REVIEW

Many studies have been carried out to assess the benefits and limitations of using industrial and construction byproducts as partial replacement of concrete mix ingredients. (Singh and Siddique, 2014) explored the potential of using coal bottom ash as partial replacement of fine aggregate (sand) in concrete. They found that at a specific water cement ratio; workability and loss of water from bleeding decreased with the use of coal bottom ash in lieu of natural sand in concrete. They also observed that the coal bottom ash concrete mixture had an improved the compressive strength by 3.5% over that of the control concrete sample, at the curing age of 28 days. The results revealed compressive strength of bottom ash concrete exceeded that of conventional concrete after 90 days. Also, the splitting tensile strength of coal bottom ash concrete increased at all the curing ages, while, the modulus of elasticity decreased at all the curing ages.

Wagih et al. (2013) discussed the possibility of replacing natural coarse aggregate (NA) with recycled concrete aggregate (RCA) in structural concrete, at different replacement proportions. They found that the concrete rubble could be utilized as recycled aggregate and used in concrete production that is suitable for most structural concrete applications in Egypt. A substantial reduction in the properties of recycled aggregate concrete (RAC) made of 100% RCA was seen when compared to that with natural aggregates, while the properties of RAC made of a blend of 75% natural aggregates and 25% RCA exhibited little change in concrete properties. In the light of their research the authors recommended the RCA in Egypt to target better environmental and economic performance in the construction industry. Also, the use of RCA reduces the surge in construction and demolition waste (CDW) quantities which cause an adverse effect on the environment.

Surya et al. (2013) studied the characteristics of recycled aggregate and RAC. They found that RCA can be used for construction of transportation infrastructure such as pavements and bridges. However, further research is needed to evaluate the long term field performance of the RAC before it can be widely utilized. (Sua-Iam and Makul, 2013) studied the feasibility of utilizing alumina waste (AW) as a partial replacement for the fine aggregate in self-compacting concrete (SCC). They evaluated the rheological and mechanical properties of the SCC mixtures based on slump flow, J-ring flow, blocking assessment, V-funnel, air content, compressive strength, and ultrasonic pulse velocity measurements. Their research concluded the following: 1) in order to maintain constant flowability, inclusion of AW required increasing the amount of the added superplasticizer; and 2) flow times for mixtures containing up to 75% AW (as a replacement for natural fine aggregates) were increased, while flow times were decreased in mixtures containing 100% AW.

(Ali and Al-Tersawy, 2012) examined the effect of using recycled glass waste as a partial replacement of fine aggregate on Self-Compacting Concrete (SCC). They found that the slump flow increased with the rise of recycled glass content. On the other hand, the compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity of recycled glass SCC mixtures decreased with the increase in the recycled glass replacement ratio. They concluded recycled glass aggregate can successfully be utilized for producing self-compacting mixes subjected to less demanding mechanical stresses. (Kosior-Kazberuk, 2011) evaluated the feasibility of using untreated ash from sewage sludge, as a lightweight replacement of natural aggregate in concrete. The research concluded that the use of this replacement strongly influence the properties of concrete. However the product can be used as structural concrete in many applications, as it achieved the required compressive strength. Rao et. al (2011) presented the results of recycled aggregate concrete beams which were prepared with different replacement proportions of recycled coarse aggregate subjected to low velocity impact. Each mix was used to prepare three beam samples of different dimensions to be tested under drop weight impact load. The results indicated that 25%

replacement of coarse aggregate does not affect the strength of concrete, and for a given impact energy the reactions and strains of recycled aggregate concrete beams with 50% and 100% replacement ratios were significantly lower and higher respectively than those of normal concrete and recycled aggregate concrete with 25% replacement ratio.

Martín-Morales et al. (2011) examined the characteristics of recycled aggregates produced from non-exhaustive production process. They performed the tests of the Spanish structural Concrete Code (EHE-08) on the aggregate, and they compared the findings with the code guideline. The results showed that none of the samples fulfilled the guidelines–of certain properties of the recycled aggregate; specifically, water absorption, sulfate content, and chloride content. However, particle shape, density, assessment of fines and resistance to fragmentation were in accordance with the code limits and recommendations. Sim and Park (2011) investigated the characteristics of concrete using recycled concrete aggregate in structural concrete members. Several samples were designed using 100% coarse recycled concrete aggregate, different replacement levels of natural aggregate with fine recycled concrete aggregate, and various levels of additional fly ash. They found that the compressive strength of mortar and recycled coarse aggregate concrete gradually decreased as the amount of the recycled materials increased. Moreover, they found that 28 days strength of the recycled aggregate concrete was greater than the design strength, with 100% replacement of coarse aggregate and 60% replacement of natural fine aggregate regardless the curing conditions and fly ash ratios. In addition, the recycled aggregate concrete displayed a significant degree of resistance to the chloride ion penetration. Accordingly, they concluded that the recycled aggregate concrete can be used in structural concrete members.

Berndt (2009) explored the suitability of using more "sustainable" concrete for wind turbine foundations and other applications involving massive quantities of concrete. In this research, the cement was replaced with substantial ratios of fly ash or blast furnace slag and by using recycled concrete aggregate. Recycled concrete aggregate was tested in conventional and slag-modified concretes. It was found that adding slag was beneficial for concrete with recycled aggregate and has the potential to reduce strength losses. Durability tests indicated insignificant increases in coefficient of permeability and chloride diffusion. Concrete with 50% fly ash replacement ratio had underperformed for the materials and mix proportions used in the study.

Ganjian et al. (2009) investigated the mechanical behavior of concrete mixtures containing 5%, 7.5% and 10% of discarded tire rubber serving as aggregate and cement replacements. They made two sets of concrete mixes. In the first set, various percentages of chipped rubber replaced coarse aggregates and in the second set, scrap-tire powder was used as a partial replacement for cement. They concluded that with up to 5% replacement, in each set, there will be no major changes on concrete characteristics, however; with larger replacement ratios significant changes will take place. Tam et al. (2008) used regression analysis to examine the relationships between recycled (crushed) demolished concrete aggregate and recycled aggregate concrete characteristics. They examined ten samples from various demolition sites, and a strong correlation was observed between the demolished concrete samples' properties and that of the recycled aggregate and recycled aggregate concrete, (i.e. the recycled aggregate concrete quality is directly proportional to that of the recycled aggregate). In addition, they claimed that recycled aggregate concrete design requirements can be developed at the initial stage of concrete demolition.

González-Fonteboa and Martínez-Abella (2007) explored the shear behavior of concrete made with recycled concrete aggregates. They performed tests on recycled aggregates and on two concrete mixes (conventional concrete and recycled concrete with 50% recycled coarse aggregates replacement proportion). They found that the deflections and the ultimate loads were slightly affected by the different types of concretes. However, in recycled concrete beams, premature cracking was detected. Evangelista and de Brito (2007) tested the replacement of fine recycled concrete aggregates with natural fine aggregates (sand) in structural concrete. They found that it is reasonable to assume that the use of fine recycled concrete aggregates does not significantly affect the mechanical properties of concrete, for replacement ratios ranging up to 30%. Khatib (2005) investigated the properties of concrete with a mix containing fine recycled aggregate. Recycled aggregate consisted of crushed concrete (CC) or crushed brick (CB) with particles less than 5 mm (0.2 inch) in diameter. The free water/cement ratio was maintained constant for all mixes. It was found that the strength was reduce by about 15-30% for concrete containing CC. However, concrete mixes containing up to 50% CB displays similar long-term strength to that of the control mix. Even at 100% replacement of fine aggregate with CB, the strength was only reduced by only 10%. In addition, it was found that there is increased occurrence of shrinkage and expansion in concrete containing CC or CB.

RESEARCH METHODOLOGY

The main focus of this research is the compressive strength of concrete after 7 and 28 days. Accordingly, 30 mixes (forming 30 specimens) were designed including 2 control mixes and 28 mixes with their traditional ingredients partly replaced with industrial and construction refuse and byproducts. Coarse to fine aggregate volumetric ratio and the water cement ratio in all of the mixes were maintained at 2:1, and 0.5 respectively. Table 1 lists the mixture ingredients and the percent reduction in cement content as well as course and fine aggregates. Six cubes were cast from each mix, to be crushed under the compressive strength test according to BS 1881-108:1983-part 108, ECP 203-2009, and ECP 203-2007 standards, on a total of 180 cubes. All of the concrete mixtures were blended for 5 minutes in a laboratory counter-current mixer. A standard mold size of 150x150x150 mm (5.9x5.9x5.9 inch) was used in the preparation of the concrete cubes to be used for the compressive strength tests.

The molds were cleaned to remove any suspended particles and then oiled along its faces before the concrete was poured into the molds. After casting the concrete cubes, these specimens were kept in the molds for 24 hours. After that, these specimens were cured in curing basins for 7 and 28 days. In addition to the compressive strength tests, two additional tests were performed on specimen no. 17, 21, and 29. The first test is the standard test for linear thermal expansion of solid materials with a push-rod dilatometer (conforming to ASTM E228-11). The second test is the standard test for water vapor transmission of materials (conforming to ASTM E96).

Insert Table 1

Utilized Materials

All materials utilized in this research were local Egyptian materials. These materials' properties conform to AASHTO, ASTM, and JIS standards and specifications.

Water

Clean tap water was used in the production of the concrete samples. Water used in mixing and curing concrete is in accordance to ES 1109:2002 specifications. The temperature of mixing water was maintained between 20-30C (68-86 °F).

Portland cement

Commercial Suez Portland Cement conforming to the requirements of Cement type V, ASTM C150/89 was used. The fineness of cement was 8% passing sieve 170 and the relative density (specific gravity) was 3.15. The initial and final setting were 2hrs and 3hrs 12 minutes, respectively.

Natural Aggregate

Natural sand from pyramids quarries Giza with a maximum particle size of 4.75 mm (0.19 inch) was used as fine aggregate. Crushed limestone from the quarries of Giza was used as coarse aggregate with a maximum nominal size of 19 mm (0.75 inch). The specific gravity of coarse and fine aggregates were 3.1 and 2.85 respectively. The fineness moduli of the coarse and fine aggregates were

5.6 and 2.6 respectively. The aggregates were tested to assure their conformance to ECP 203-2009, ES 1109:2002, BS 812 part 110-1990, ASTM C25-98.

Crushed concrete (as replacement for coarse and fine aggregates)

Crushed concrete was obtained from remnants of concrete test cubes that were used in compressive strength tests in Cairo University materials testing labs. The types of aggregates utilized in preparing these cubes were crushed limestone as coarse aggregate, and natural sand as fine aggregate. The cement content of the crashed cubes ranged from 300 to 400 kg per cubic meter. The cubes were cracked at compressive stresses ranging from 20 to 30 MPa (2900.74-4351.11 psi). The fine particles with a maximum size of 4.75 mm (0.19 inch) were used as fine aggregate replacement in specimen no. 7, 8, 9, and 10. While larger particles with a maximum nominal size of 19mm were used as coarse aggregate replacement in specimen no. 3, 4, 5, and 6.

Air cooled blast furnace slag (ACBFS)

Locally available ACBFS in Egypt (from Ezz-Steel Alexandria plant) with maximum nominal size of 18 mm was used as coarse aggregate replacement in specimen no. 11, 12, 13, and 14. The ACBFS was tested to conform to the requirements of type B aggregate specified by JIS A 5011.

Silica fume

Locally available silica fume in Egypt with a surface area of 20,000 m^2/kg (97580 ft^2/lb), and relative density of 2.35 was used as cement replacement in specimen no. 15, 16, 17, and 18. The used silica fume was tested to conform to ASTM C 1240.

Fly Ash

Locally available fly-ash in Egypt with a surface area ranging from 270 to 320 m^2/kg (1317 to 1561 ft^2/lb), and bulk density of 650 kg/m3 was used as cement reduction in specimen no. 19, 20, 21, and 22. The used fly ash was tested to conform to the requirements of class C fly ash specified by ASTM C 618 (AASHTO M 295).

Ground Granulated Blast Furnace Slag (GGBFS)

Locally available GGBFS in Egypt (from Ezz-Steel Alexandria plant) with a surface area of 500 m2/kg and bulk density of 1150 Kg/m3 was used as cement replacement in specimen no. 23, 24, 25, and 26. The used GGBFS was tested to conform to the requirements of Grade 100 slag specified by ASTM C 989 (AASHTO M 302).

Metakaolin (MK)

Locally available MK in Egypt with an average particle size of about 1 to 2 micrometers was used as cement reduction in mixes no. 27, 28, 29, and 30. The used MK was tested to conform to the requirements of Class N pozzolans specified by ASTM C 618 (AASHTO M 195).

RESULTS AND DISCUSSION

This section ~~is~~ investigates the effects of each additive or partial replacement of the different components. Table 2 summarizes all the cubes compressive strength, slump, temperature tests and measurement~~s~~ results. In the following sections, these results will be discussed in details. For the purpose of simplicity, all test results will be displayed in two groups. The first group (Group 1) contains the specimens with cement content equals to 350 kg/m^3 (21.9 lb/ft^3), and the second group (Group 2) contains the specimens with cement content equals to 450 kg/m^3 (28.1 lb/ft^3).

Insert Table 2

Slump test

A Slump Test was performed to measure the stiffness and consistency of the fresh concrete. Figure 1 displays the average slump test results for the 2 groups of samples. It is observed that Group 2 specimens have a higher workability rate than Group 1. -This is due to the higher water and cement content in Group 2 specimens. According to the general rule, as cement content increases, slump also increases due to the increase in the water when the cement content increases, hence leading to increased workability (Marar and Eren 2011).

Insert Figure 1

Since the aggregate takes up more than 70% of the total concrete volume, its constituent have a significant effect on physical-mechanical properties of concrete. Hence, replacing the fine and coarse natural aggregates with crushed concrete was found to have higher workability. This can be attributed to the less water absorption of the freshly crushed concrete cubes that were used to produce the recycled aggregates. This less absorption resulted in higher free water content in mixes no. 3 to 10, than that of the base mixes (i.e. specimen no. 1 and 2).

The increased workability of the rest of the mixes with differentiated proportions than the base mixes conform with the literature that indicates higher workability levels, when replacing portion of the mix cement with pozzolanic materials such as Silica Fume, Fly Ash, GGBS, and Metakaolin, or replacing portions of the coarse aggregates with ACBFS. The slump is directly affected by the surface area. For large surface area such as silica fume, a large portion of water content is needed to cover this surface area and thus will result in decreasing the workability of concrete. As shown in Figure 1, the mixtures that contain the silica fume with surface area equals to 20,000 kg/m^3 (1,249 lb/ft^3) have lower slump values than the remaining mixtures that have GGBFS, Mk and fly ash respectively. Also, the slump is directly proportional to the maximum nominal size of coarse aggregate. In addition, increasing the maximum nominal size leads to increasing slump value. Therefore, as shown in Figure 1, replacing the natural coarse aggregate with a maximum nominal size of 19 mm (0.75 inch), a nominal by the ACBFS with a maximum nominal size 18 mm (0.71 inch) leads to increasing the workability of concrete.

Compressive strength Test

Mechanical behavior of all the mixes was studied by compression tests with curing times of 7, and 28 days. Results obtained are reported in Figure 2. The following sections discuss and analyze the compressive strength test results compared to those of the control mixes (specimen no.1 for Group 1, and Mix no. 2 for Group 2) based on the type of the replacement material.

Insert Figure 2

Recycled Coarse Aggregate

When coarse aggregate is replaced with recycled coarse aggregates; there is an increase in the compressive strength of Group 1 mixes for 7 and 28 days. This increase is proportional to increase of the replacement percentage. This can be attributed to the less absorption rates of the recycled aggregate than that of the natural aggregate, which results in fewer cracks around the aggregates, which in turn increase the cohesion of the mix.

However, in Group 2 mixes, there is a decrease in the 7 days compressive strength. For the 28 days compressive strength, it is noted that with 25% replacement ratio, there is a slight increase in strength, however, there is a large decrease in strength when the replacement ratio is 50%. This can be attributed to the less absorption rates of the recycled aggregate, which results in an increased amount of free water content (i.e. greater w/c ratios), which in turn decreases the overall strength of the mix, that factor is very clear when the replacement ratio reached 50%.

Accordingly, it is advised to use recycled coarse aggregates with ratios not exceeding 25% of the natural coarse aggregates, and decrease the w/c ratio in mixes with high cement content.

Recycled Fine Aggregate

When fine aggregate is replaced with recycled fine aggregates; there is a slight increase in the 7 days compressive strength, coupled with an average 9% decrease in the 28 days compressive strength. This can be attributed to the higher absorption rates of the recycled fine aggregates than that of the natural sand, which in turn absorbed much free water which decreased the w/c ratio at 7 days, resulting in higher compressive strength. However, when much water is absorbed the cement reactions were hindered at later dates (i.e. 28 days), providing weaker mix. For Group 2 mixes, the same phenomena is amplified due to the increase in the cement content, which increases the free water demand, and this is very clear when the replacement ratio reaches 25%. Accordingly, it is advised to use recycled fine aggregates with ratios not exceeding 10% of the natural fine aggregates, and increase the w/c ratio in mixes with high cement content.

Air Cooled Blast Furnace Slag (ACBFS)

When coarse aggregate is replaced with ACBFS; there is an increase in the 7 day, and 28 day compressive strength of Group 1 and Group 2 mixes.–This increase appears to be irrelevant to the increase in the replacement percentage, except in 7 day strength. Also, the increase in strength decreases as the cement content increases (i.e. from ~22% in Group 1, to ~12% in Group 2). This can be attributed to the slightly better mechanical characteristics of the mixed ACBFS and natural aggregates than that of the pure natural coarse aggregate, which effect diminish as the mix get stronger (i.e. increase cement content). Accordingly, it is advised to replace more than 20% of the natural coarse aggregates with ACBFS to achieve better mechanical characteristics of the mix which conforms with the results obtained from the literature.

Silica Fume

When replacing portion of the cement content of the mix with Silica fume while maintaining the w/c ratio constant (and accounting only for the pure cement content) the 7 days and 28 days compressive strength of the concrete mix increase for both groups of mixes. However, the increase in strength is larger in Group 1 mixes.-This can be attributed to the limiting effect of using silica fume in mixes with higher cement content.

Accordingly, it is advised to use silica fume as a replacement of cement with ratios not exceeding 12%, while maintaining the cement content of the mix below 450 kg/m3 (28.09 lb/ft^3) to achieve the full benefits of the replacement.

Fly Ash and Metakaolin

Using any of those pozzolanic materials as a cement replacement should have similar effect on the 28 days compressive strength to that of silica fume according to the literature. However, this was not observed in this research because the w/c ratio was maintained constant (hence the water content was based only on the pure cement content) which resulted in a large decrease in the mix free water when using fly ash at percentages of 20 to 30%. This in turn hindered the benefits obtained from using fly ash as a cement replacement or as a pure additive. Accordingly, it is advised to link the w/c ratio to both the cement and cement-substitute content when substituting cement with percentages more than 12%.

Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS has the benefits of other pozzolanic materials when used as cement replacement; however, in this research the 7 and 28 days compressive strength of both groups of mixes was greatly reduced.

This can be attributed to the great ratios in which GGBFS was used (i.e. 50%, and 70%) which caused a decrease in the water content by 50% to 70% respectively, because in this research the w/c ratio was maintained constant and based only on the pure cement content.

Accordingly, it is advised to link the w/c ratio to both the cement and cement-substitute/replacement content when substituting cement with percentages more than 12%.

Concrete Durability

The durability of concrete refers to its ability to resist any process causing any deterioration and hence to retain its original shape, quality, dimension, and serviceability in the working environment during its anticipated operational life (Sadek &. El-Attar 2012). For that, to maintain the durability of concrete, two tests were conducted; linear thermal expansion and water vapor transmission.

Linear thermal expansion

The thermal behavior and thermal durability of green concrete at high temperature was studied by determining the expansion rate for concrete samples due to exposure into this temperature. For the test evaluation, a concrete slab 2cm x 2cm x 20 cm (0.79 inch x 0.79 inch x 7.9 inch) was prepared from specimen no. 29 to assess its performance against the requirements of the ASTM E228-11 standard test titled "standard test method for linear thermal expansion of solid materials with push rod dilatometer.

For this test, the sample was connected to a mechanical dial gauge (0.01 mm accuracy) and fixed inside a heated chamber. Different readings were taken during the heating period from the room temperature up to nearly 100 degrees. Using these measures, the coefficient of thermal expansion was computed. The coefficient of thermal expansion was found be of a value of 15.5x10E-6. However, this coefficient is higher than that of traditional concrete (i.e. ~12 * 10E-6). Aggregate type has an influence on the thermal expansion of the concrete. The lime stone that was used in this sample mixture has a relative minimum thermal expansion coefficient due to its porous structure. Usinge Metakaolin as a substitute material for cement has an effect on increasing the thermal expansion of concrete. The presence of Metakaolin helped in decreasing the void ratio that led to an increase in thermal expansion, however; it meets the requirements of the ASTM E228-11 standard test.

Water vapor transmission

For the test evaluation, a concrete cylinder of 5.5 cm (2.2 inch) diameter and 2 cm (0.79 inch) length was prepared form specimen number 29 to assess the performance of concrete and to demonstrates that concrete material meets or exceeds the requirements of ASTM standard E96 entitled "Standard Test Method for Water Vapor Transmission of Materials".

The test determines the water vapor transmission (WVT) of materials whereas this is an important characteristic in determining durability. The test can be performed on specimens that do not exceed 32 mm in thickness. A desiccant test method was adopted to measure permeance; with low humidity on one side and high humidity on the other. The conducted water vapor transmission test is performed to assess the following:

- Water vapor permeability: is the time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions.
- Permeability: is associated with the property of a material, but the permeability of a body that performs like a material may be used. Permeability is the arithmetic product of permeance and thickness.
- Water vapor permeance: is the time rate of water vapor transmission through unit area of flat material or construction induced by unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions. Permeance is a performance evaluation and not a property of a material.

The test results were as following:

- Water vapor transmission = 3.94*10E4 (microgram/m^2.s)
- Permeance = 1.6*10E2 (nanogram/Pa.s.m^2) (2.8 US perm)
- Permeability = 2.97 (ng/Pa.S.m) (0.0519 US perm)

Accordingly, this mix classifies as a water retarder mix, and meets the requirements of the ASTM E96 standards.

CONCLUSIONS

Experimental work done in this research investigated the effect of industrial refuse and by products (as substitution of cement or aggregate) on the physical-mechanical properties of green concrete produced. This research results indicated a positive effect on compressive strength when cement was partially replaced with pozzolanic industrial refuse and byproducts locally available and produced in mass quantities in Egypt. Further, the research is concerned with the usage of demolition refuse to be recycled and used as a replacement for natural fine and coarse aggregates. The major research findings are:

a) Regarding coarse aggregate partial replacement:
   - It was found that using crushed concrete as coarse aggregates replacement with ratios up to 50% enhances the compressive strength of mixes with cement content not greater than 350 kg/m^3 (21.85 lb/ft^3) by more than 30%, which is a very promising ratio.
   - However, when used in high cement content mixes (i.e. cement content = 450 kg/cm^2 (6401 psi) it is not recommended to increase the percentage of replacement greater than 25%. Therefore, it is practical to use recycled concrete aggregate which is produced by recycled crushed concrete refuse in order to reduce the consumption of natural aggregate and the amount of concrete refuse which eventually ends up in landfills.

b) Utilizing demolition refuse as a replacement for fine aggregates is not recommended as their use reduces the compressive strength of concrete mix by more than 10%.

This research did not assess the interaction between concrete mixtures and reinforcement, which is recommended for future research. Other future research aspects should include the assessment of utilizing plastic refuse as an aggregate replacement.-This research also investigated the sustainability benefits of using demolition and industrial refuse as a replacement for aggregates and cement in traditional concrete mixes. Future research can investigate the obtained results and prove they are statistically significant, considering that there is a reasonable number of concrete mixes/specimens.

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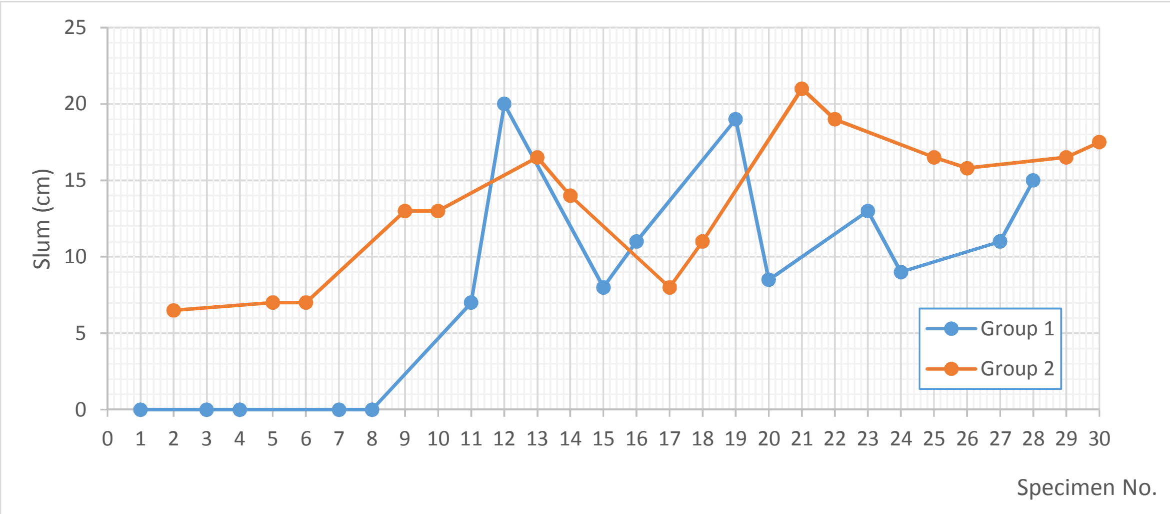
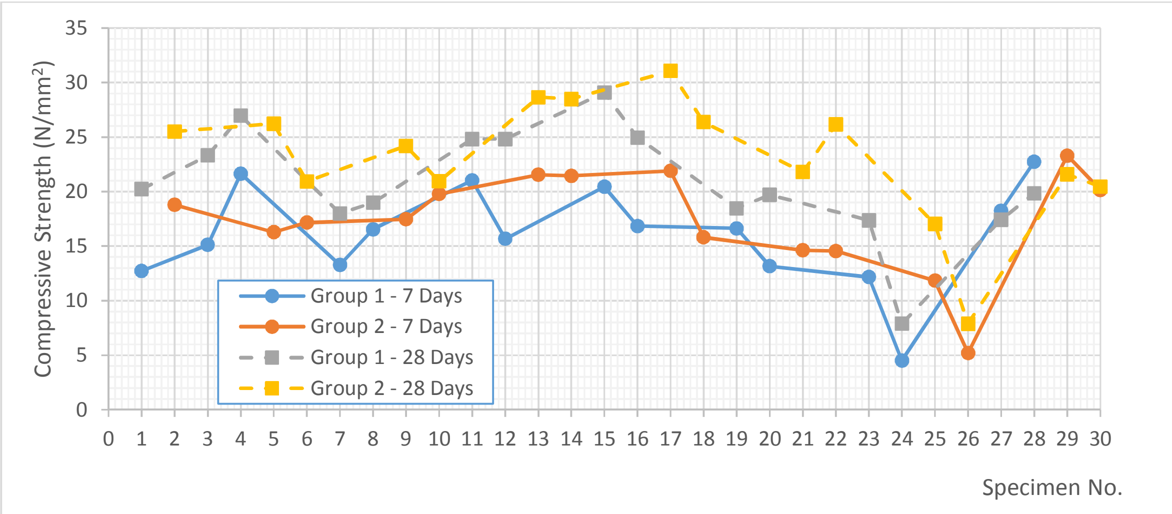
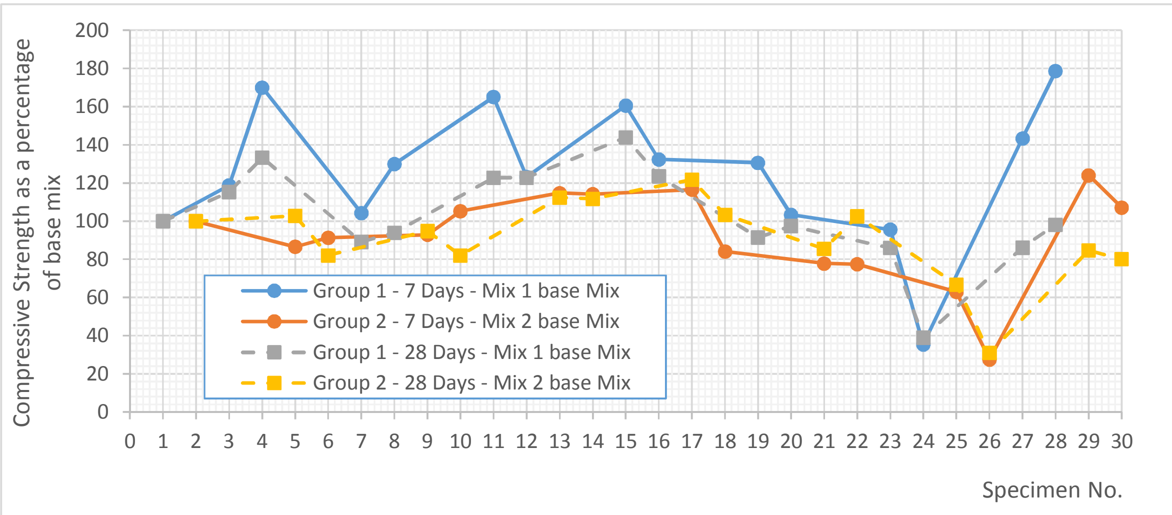


Figure 1: Slump test average results



a) Compressive strength



b) Compressive strength as a percentage of base mix

Figure 2: Compressive strength and Compressive Strength as a percentage of base mix

Table 1: Design mixes

Specimen ID	Replacement Material	Cement Content (kg/ m³)	Reduction (%)			Cement (kg)	Cement Replacement (kg)	Course Aggregate (kg)	Course Aggregate Replacement (kg)	Fine Aggregate (kg)	Fine Aggregate Replacement (kg)	Water (kg)
			Cement	Course Aggregate	Fine Aggregate							
1	Base Mix	350	---	---	---	10.9	0	34.1	0.0	21.7	0.0	5.4
2	Base Mix	450	---	---	---	14.0	0	34.1	0.0	21.7	0.0	7.0
3	RCA	350	---	25	---	10.9	0	25.6	8.5	21.7	0.0	5.4
4	RCA	350	---	50	---	10.9	0	17.1	17.1	21.7	0.0	5.4
5	RCA	450	---	25	---	---	---	---	---	---	---	---
6	RCA	450	---	50	---	14.0	0	17.1	17.1	21.7	0.0	7.0
7	RFA	350	---	---	10	10.9	0	34.1	0.0	19.5	2.2	5.4
8	RFA	350	---	---	25	10.9	0	34.1	0.0	16.3	5.4	5.4
9	RFA	450	---	---	10	14.0	0	34.1	0.0	19.5	2.2	7.0
10	RFA	450	---	---	25	14.0	0	34.1	0.0	16.3	5.4	7.0
11	ACBFS	350	---	25	---	10.9	0	25.6	8.5	21.7	0.0	5.4
12	ACBFS	350	---	50	---	10.9	0	17.1	17.1	21.7	0.0	5.4
13	ACBFS	450	---	25	---	14.0	0	25.6	8.5	21.7	0.0	7.0
14	ACBFS	450	---	50	---	14.0	0	17.1	17.1	21.7	0.0	7.0
15	S Fume	322	8	---	---	10.0	0.8	34.1	0.0	21.7	0.0	5.4
16	S Fume	308	12	---	---	9.5	1.1	34.1	0.0	21.7	0.0	5.3
17	S Fume	414	8	---	---	12.8	1.0	34.1	0.0	21.7	0.0	6.9
18	S Fume	396	12	---	---	12.3	1.5	34.1	0.0	21.7	0.0	6.9
19	Fly Ash	280	20	---	---	8.7	1.7	34.1	0.0	21.7	0.0	5.2
20	Fly Ash	245	30	---	---	7.6	2.3	34.1	0.0	21.7	0.0	4.9
21	Fly Ash	360	20	---	---	11.2	2.2	34.1	0.0	21.7	0.0	6.7
22	Fly Ash	315	30	---	---	9.8	2.9	34.1	0.0	21.7	0.0	6.3
23	GGBFS	175	50	---	---	5.4	2.7	34.1	0.0	21.7	0.0	4.1
24	GGBFS	88	75	---	---	2.7	2.0	34.1	0.0	21.7	0.0	2.4
25	GGBFS	225	50	---	---	7.0	3.5	34.1	0.0	21.7	0.0	5.2
26	GGBFS	113	75	---	---	3.5	2.6	34.1	0.0	21.7	0.0	3.1
27	MK	280	20	---	---	8.7	1.7	34.1	0.0	21.7	0.0	5.2
28	MK	245	30	---	---	7.6	2.3	34.1	0.0	21.7	0.0	4.9
29	MK	360	20	---	---	11.2	2.2	34.1	0.0	21.7	0.0	6.7
30	MK	315	30	---	---	9.8	2.9	34.1	0.0	21.7	0.0	6.3

Notes: RCA: is recycled coarse aggregate; RFA: is recycled fine aggregate; ACBFS: Air-cooled blast furnace slag; S Fume: silica fume; GGBFS: is ground granulated blast furnace slag; MK: metakaolin.

1 kg/m³=0.0624 lb/ft³, 1 Kg=2.2046 lb

Table 2: Results of fresh and hardened concrete tests

Specimen ID	7 days - Sample Weight (N)			7-days strength (N/mm^2)			28 days - Sample Weight (N)			28 days -strength (N/mm^2))			Slump (cm)	Temp. (°c)
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3		
1	79.11	78.68	75.90	12.01	14.63	11.56	78.51	80.39	80.65	16.94	22.01	21.7	0	28.9
2	80.33	78.72	80.37	17.74	19.83	18.81	79.90	79.16	80.10	24.80	24.28	27.45	6.5	30.9
3	79.17	78.63	77.50	14.99	15.21	15.16	79.67	78.47	81.65	29.03	21.13	19.76	0	30.3
4	78.78	80.01	82.59	16.63	24.9	23.43	78.81	76.74	80.1	25.04	28.01	27.79	0	30.7
5	79.63	77.21	76.75	12.32	17.74	18.77	76.09	77.64	77.37	24.81	22.94	30.90	7	30.5
6	77.71	76.72	76.89	15.12	18.01	18.37	76.84	76.01	74.87	23.52	22.99	16.28	7	30.6
7	77.79	76.82	77.57	13.92	13.25	12.63	77.73	77.12	78.51	19.39	17.3	17.34	0	28
8	7674	82.38	78.57	16.36	16.1	17.16	80.83	79.6	77.05	21.74	19.21	16.01	0	30.8
9	79.68	78.53	82.02	18.68	19.74	13.96	79.9	79.34	81.05	23.61	20.53	28.41	13	30.4
10	82.61	79.34	79.74	22.68	18.37	18.28	80.52	77.48	79.89	23.57	19.64	19.61	13	30.6
11	82.21	82.51	83.83	25.88	14.85	22.32	83.22	82.62	82.53	26.36	24.81	23.29	7	30.6
12	86.06	85.07	84.53	16.5	14.45	16.1	83.22	82.62	82.53	26.36	24.81	23.29	20	30.6
13	84.47	82.41	82.07	18.63	23.34	22.68	84.96	84.25	85.4	20.9	27.3	37.75	16.5	29.3
14	83.14	83.07	82.95	20.45	25.08	18.81	86.89	86.92	83.88	21.74	32.77	30.95	14	30.8
15	79.27	79.83	80.11	16.99	21.3	23.03	78.52	80.81	77.32	25.12	35.66	26.46	8	29.4
16	78.72	77.99	78.55	18.32	14.76	17.48	77.81	78.75	79.07	22.24	32.86	19.79	11	31
17	81.7	81.93	81.69	17.06	26.46	22.19	79.02	80.15	79.96	30.5	30.37	32.3	8	34
18	81.38	79.62	78.27	15.43	18.54	13.47	79.74	77.83	77.25	31.48	25.43	22.19	11	32.5
19	76.64	77.99	76.21	13.43	19.74	16.72	78.54	80.09	79.04	16.41	20.85	18.19	19	31.3
20	80.37	81.53	78.23	12.32	15.83	11.34	79.4	80.86	79.37	20.45	21.25	17.39	8.5	32.7
21	81.00	78.53	80.54	15.52	12.59	15.79	78.81	80.29	79.74	19.65	23.57	22.19	21	32.7
22	81.45	84.63	79.71	13.93	15.61	14.14	81.13	80.45	79.87	26.99	25.26	26.23	19	32
23	79.13	78.3	80.27	11.64	11.7	13.16	79.68	78.73	81.58	15.43	15.88	20.81	13	31
24	80.57	77.68	76.72	4.81	4.45	4.27	79.31	79.61	78.73	7.65	8.1	7.96	9	30.9
25	79.18	81.76	80.43	11.29	13.61	10.63	81.87	82.65	77.01	19.3	15.52	16.23	16.5	32
26	80.68	79.69	79.86	5.12	5.41	5.03	78.55	78.76	81.71	6.67	7.78	9.21	5.8	32.8
27	80.18	79.98	78.64	20.41	17.18	17.17	78.72	69.32	77.48	17.08	17.7	17.48	11	31.4
28	79.57	78.99	79.15	21.1	28.33	18.79	78.39	80.67	77.7	23.52	18.01	18.01	15	31.2
29	77.08	81.41	79.93	22.74	26.8	20.37	76.7	79.51	76.99	20.36	20.59	23.83	16.5	32.3
30	80.6	78.04	79	22.38	21.85	16.19	77.11	76.9	79.02	16.99	19.61	24.72	17.5	31.5

Notes:
1 N=0.2247 lb, 1N/mm^2=145.037 psi (pound per square inch), 1 cm=0.03281 ft, °c= (°F-32)*(5/9)