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A study on strength and durability of self-compacting concretes made of recycled aggregates

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Abstract

Given the development of construction industry and design and implementation of high rise buildings with complex sections and various geometrical forms, the use of self-compacting concretes has received the attention of construction engineers and provided great advantages. Due to the increasing air pollution in cities, governments encounter the important issue of repelling the pollutants in which construction industry plays a key role; so that recycled concrete has been suggested to decrease the construction pollutants. Therefore, self-compacting recycled concrete can take advantage of the both types of concrete and enormously benefit the environment by decreasing the use of natural aggregates and preventing from deterioration of natural mines The most important properties of good concrete include its workability, strength and durability. The range of these three properties is determined for the concrete made according to EFNARC, ASTM and BS through fresh concrete tests including slump flow, V-funnel, J-ring, L-box, compressive strength, capillary water absorption and water penetration under pressure and the following results are gained. Increasing the amount of recycled aggregates resulted in reduction of self-compacting concrete criteria like slump, J-ring, etc. which indicated decline of plasticity, workability, passing ability and so on and that might be because of grading variations. Compressive strength was dramatically reduced by increasing the amount of coarse recycled aggregate so that compressive strength of concrete specimens declined by 2-10% as the amount of recycled aggregate rose from 25% to 100%. Increasing the amount of recycled aggregates generally enhanced percentage of capillary water absorption; so that according to the results of tests, water absorption rose by 5-15% in specimens by increasing percentage of recycled aggregates, indicating an increase in permeability and a decrease in durability of concrete. The main propose of this article is to determine the optimum replacing percentage of recycled aggregates to find the best compressive strength and durability of self-compacting concrete. Therefore, different samples with replacing recycled aggregates by 0%, 25%, 50%, 75% and 100%, water to cement ratio of 0.35 and 0.45 and different amount of super- plasticizer were. The result shows that by increasing in the amount of recycled aggregates, the strength of concrete decreases while the permeability of concrete reduces.

Keywords: Self-Compacting Concrete, Recycled, Strength, Permeability, Durability

1. Introduction

According to the research conducted in the early twenty-first century, 5.5 billion tons of concrete is annually used over the world and aggregates form about 60% to 80% of the concrete by volume [1]. Therefore, aggregates are of great importance in terms of the material, quality, amount and size. On the other hand, billions of tons of stone materials are utilized to produce the aggregates, mostly extracted from natural sand mines. Given the ending of expected life of buildings constructed in last decades and development of cities in term of renovation, a vast sum of concrete construction debris has been left inthe nature by destruction of old buildings, causing a threat to the environment; so that recycling and reusing such materials for construction may help reduce the environmental deterioration enormously.

Self-compacting concrete was first introduced in 1986 by Okamora, a Japanese scientist and in 1988, two Japanese scientists named as Ozaka and Makava produced the concrete in laboratory; the research was then continued in the USA, Canada and European countries and in 2002, the European foundation of EFNARC conducted a study in this

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regard and presented a guide to self-compacting concrete [2, 3].
Carro et al (2015) suggested that there would not be a considerable change in strength of self-compacting recycled concrete with 20% of gradients replaced by recycled aggregate but compressive strength dramatically decreased by more than 50% substitution so that criterion of strength had to be measured for such concrete [4]. Other research conducted recently showed that using coarse recycled aggregate (gravel) led to a decrease in density and compressive strength of the concrete and an increase in its permeability, based on the amount used [5]. Conversely, the use of fine recycled aggregate (sand) had trivial effects on strength characteristics of the concrete [6].
The study aims to determine variations in strength and permeability of self-compacting concretes with different substitution percentages of coarse recycled aggregate (gravel) and conduct permeability tests seeking to achieve technical results of electrical resistance, capillary water absorption and water penetration under pressure.

2. Description of experiments

2.1. Materials

It is attempted to employ ordinary materials available within the region which are used in construction projects; so that the materials can be conveniently supplied at a low cost.
Properties of used materials are as follows:

- **Cement**

The ordinary type II Portland pozzolan cement is used in most of construction projects. So type II Portland pozzolan cement is applied in the study according to Table 1.

Table 1 Properties of type II cement

Test	Density(gr/cm^3)	Blaine (gr/cm)	28-day compressive strength(kgf/cm^2)
Type II cement	3.21	3081	492

- **Aggregates**

Physical and mechanical properties of aggregates have a substantial effect on characteristics of the concrete; so their type, quality, etc. must be determined by various experiments. Recycled aggregates are provided from the concrete made in construction site [7].Water absorption and grading tests, essential to prepare the mix design, has been done according to ASTM C33-17-128 on natural and recycled aggregates. Results of the tests are presented in term of a diagram in Figure 1 and 2.

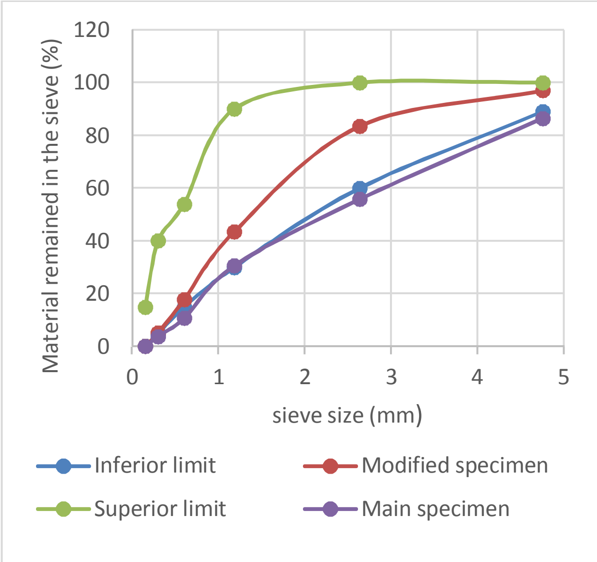

Figure 1. Diagram of sand grading

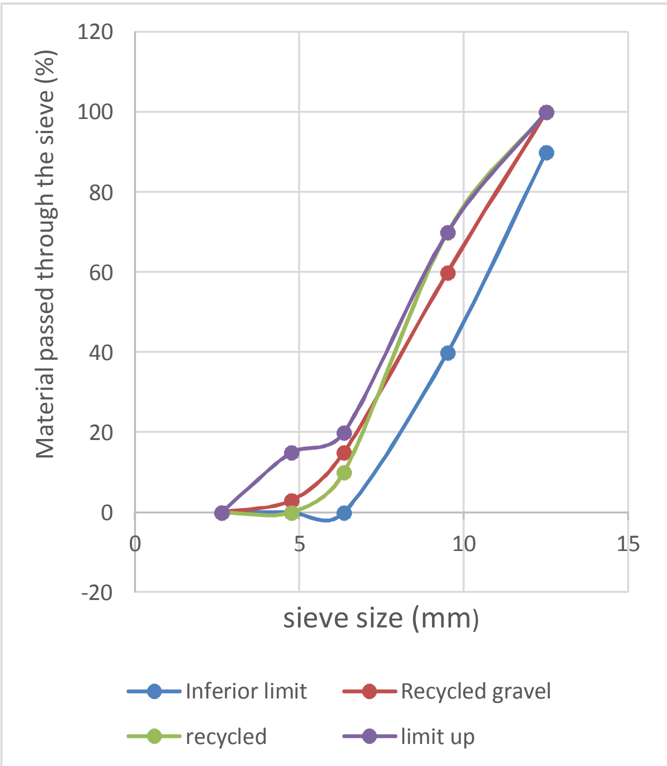

Figure 2. Grading diagram of natural and recycled gravel

According to the results of grading test (Figure 1), existing fine aggregates (sand) do not have proper grading lacking fine-grained particles; so that rock flour is added by about 10% of total weight of aggregates in order to modify gradation. Rock flour is utilized for modification of fine aggregate grading.

To produce self-compacting concrete, coarse aggregates (gravel) up to 12 mm in diameter were used.

According to the results listed in Table 2 and variations in weight values, percentage of water absorption by aggregates is considered 3% on average in each mix design.

Table 2: Results of water absorption test on aggregates

Aggregate	Sand	Gravel	Recycled gravel
Absorption percentage	2.7	1.5	3.5

- **Water**

Drinking water is used for mix design. It is best touse distilled water for concrete. It is recommended to apply drinking water because it contains far less salts and characteristically resembles distilled water.

2. 2. Mix design

Table 3 represents 10 initial proposals for mix design that are prepared based on mix designs presented in previous studies and a series of pilot projects carried out in the construction site, including maximum size (diameter) of coarse aggregate up to 20 mm; percentage of coarse aggregates out of total weight of aggregates about 30% to 40% [8, 9]; two water-cement ratios by 0.35 and 0.45 as necessary criteria of research objectives; and substitution of recycled aggregates by 0%, 25%, 50%, 75% and 100%.

Table 3: Properties of mix designs for self-compacting recycled concrete

Item	Mix design name	Cement (Kg)	Water (lit)	Gravel (Kg)	Sand (Kg)	Rock flour (Kg)	Superplasticizer
1	M.3500	500	175	508	1067	118	0.7
2	M.3525	500	175	508	1067	118	0.7
3	M.3550	500	175	508	1067	118	0.7
4	M.3570	500	175	508	1067	118	0.6
5	M.35100	500	175	508	1067	118	0.5
6	M.4500	450	202.5	677	900	116	0.5
7	M.4525	450	202.5	677	900	116	0.5
8	M.4550	450	202.5	677	900	116	0.5
9	M.4575	450	202.5	677	900	116	0.4
10	M.45100	450	202.5	677	900	116	0.35

- **Number and size of specimens**

According to the research objectives and tests listed for each mix design, concrete must be prepared in two steps. At first step, 12 liters of concrete is produced to conduct self-compacting concrete experiments such as slump flow test, T50 test, V-funnel test, L-box test and J-ring test.

At second step, 6 cube specimens of 10 × 10 ×10cm are needed to determine compressive strength, electrical resistance and capillary water absorption and 3 cube specimens of 15 × 15 × 15cm are required for calculation of water penetration under pressure.

3. Analysis of the results

3. 1. Tests on fresh concrete

Preparation of self-compacting concrete must fulfill specific criteria so that the study is based on EFNARC Specification and Guidelines for Self-Compacting Concrete [10].

In title of mix design, first two numbers refer to water-cement ration and second two numbers refer to the percentage of recycled aggregates.

Experiments such as slump flow test, T50 test, J-ring test, V-funnel test and L-box test are carried out to determine properties of fresh self-compacting concrete. The range of results should be in accordance with EFNARC guidelines listed in Table 4. The results of fresh concrete tests are illustrated in Figure 3 and according to the diagrams, an obvious decrease is observed in workability, plasticity and passing ability by enhancing the amount of recycled aggregates.

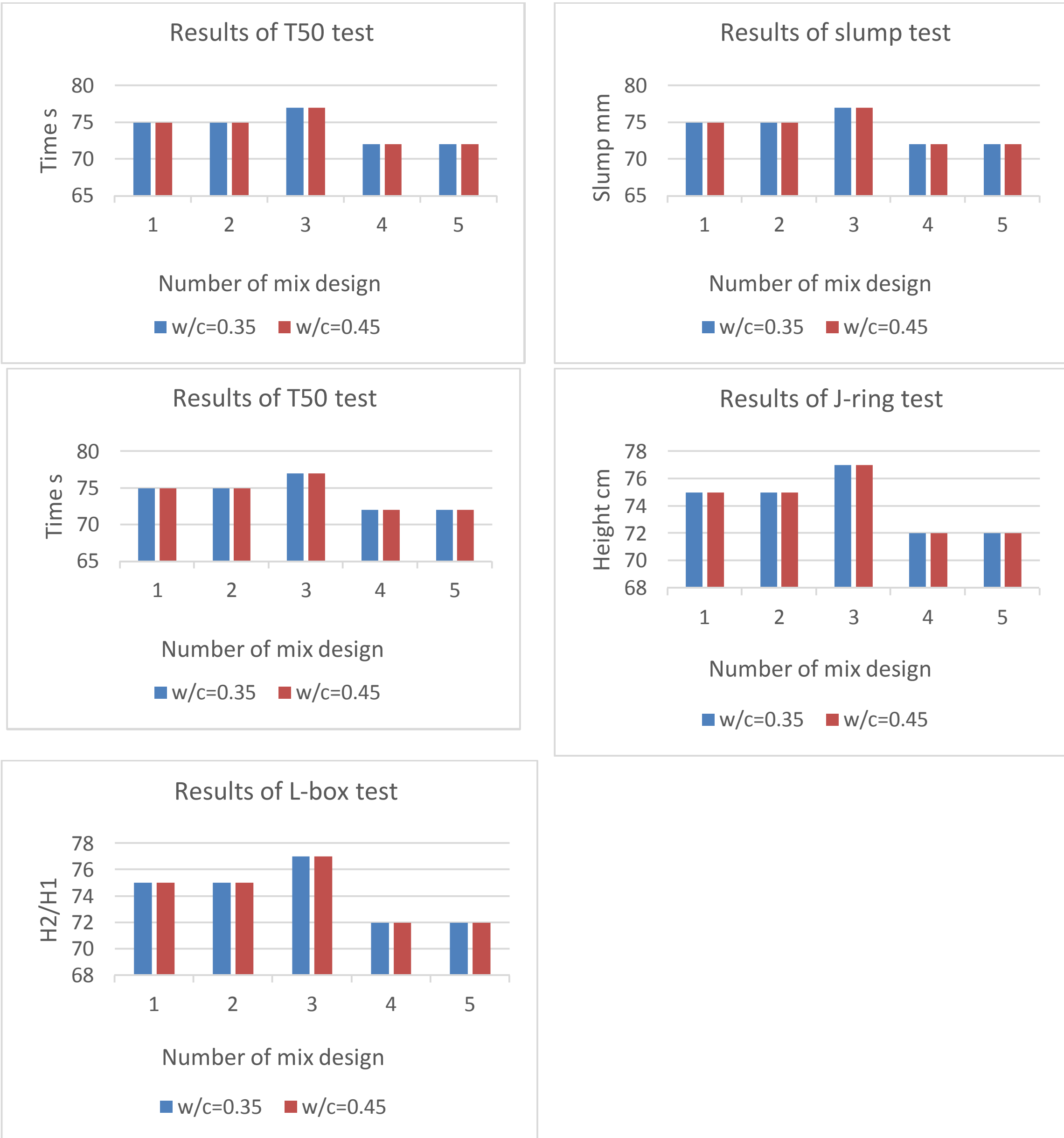

Figure 3.workability tests results on fresh concrete

Table 4: The allowable range of results on fresh concrete according to EFNARC

Test method	Test objective	Unit	Minimum value	Maximum value
Slump flow	Plasticity and filling ability	mm	650	800
T50	Plasticity and filling ability	s	2	5
J-ring	Passing ability	mm	0	10
L-box	Passing ability	H2/H1	0.8	1.0
V-funnel at T5min	Segregation resistance	s	0	3
V-funnel	Filling ability	s	6	12

3. 2. Strength and durability tests on 28-day specimens

- **Electrical resistance**

This test is done in order to determine durability of concrete so that electrical resistance of specimen increases as its porosity declines and the trend is directly related to the specimen's permeability; as porosity of concrete decreases, its permeability declines and its durability increases consequently. Electrical resistance has a direct relation with cement content, aggregate grading and the amount of recycled aggregates; so that as aggregate grading improves and the voids of aggregates is filled more properly by plastic concrete, porosity of hardened concrete decreases and electrical resistance rises [5, 8]. Tests are conducted according to ASTM C-1202 and the results are listed in Table 5. Electrical strength decreases by increasing the amount of recycled aggregates in various mix designs, which refers to an increase in porosity and permeability of concrete. Descending trend of the criterion is shown in Figure 4. Evidently, decline of water-cement ratio has a significant impact on electrical resistance of specimens.

Table 5: Results of electrical resistance tests

mix design	M.3500	M.3525	M.3550	M.3575	M.35100	M.4500	M.4525	M.4550	M.4575	M.45100
Electrical resistance (Ω)	374	366	341	315	297	321	310	294	298	274
Specific electrical resistance (Ω,m)	37.4	36.6	34.1	31.5	29.7	32.1	31.0	29.4	29.8	27.4

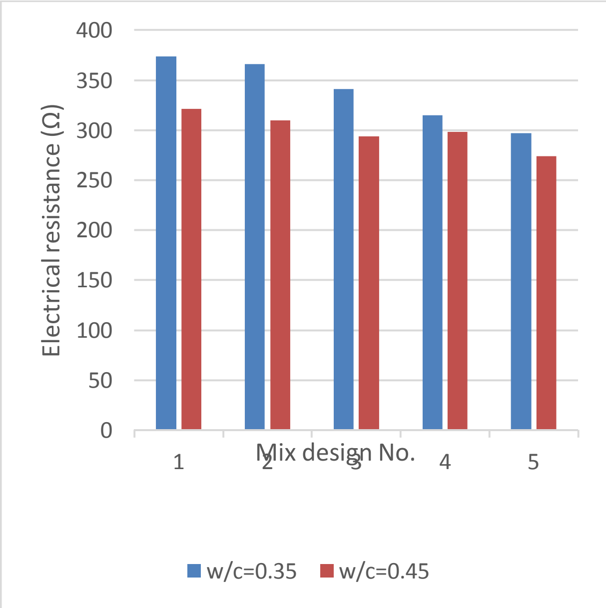

Figure 4. Diagram of comparisons between results of electrical resistance tests

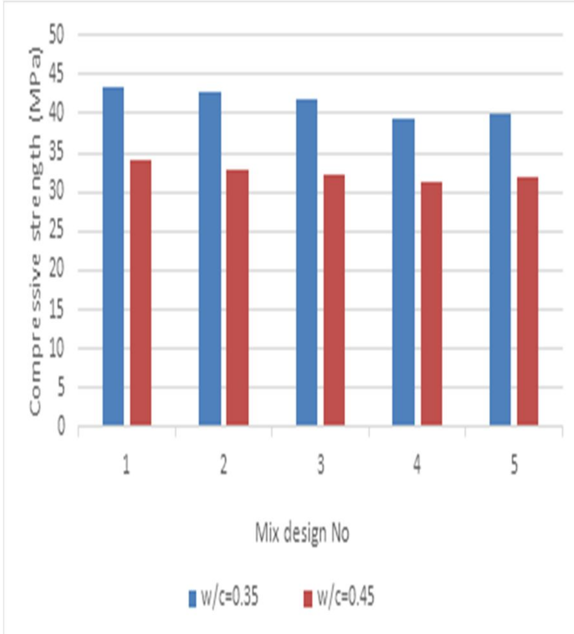

Figure 5. Diagram of compressive strength

- **Compressive strength**

Compressive strength is one of the most important criteria for assessment of concrete. So the concrete would have better quality if its compressive strength falls less by increasing the amount of recycled aggregates. The compressive strength test is done according to ASTM C39 and Table 6 represents mean results of 3 specimens [4, 11]. Figure 5 illustrates a comparison between variations of compressive strength vs variations of water-cement ratio and increasing the amount of recycled aggregates; so that compressive strength falls as water-cement ratio and amount of recycled aggregates increase.

- **Capillary water absorption**

Based on ASTM C642, the test aims to determine permeability and durability of concrete against external aggressive materials; so that permeability rises and durability declines as depth and rate of water penetration increases in concrete. Since specimens are kept in oven for 24 hours to get dry, water absorption is likely to increase.
due to emergence of tiny cracks as a defeat of the

Table 6. Results of compressive strength test

mix design	M.3500	M.3525	M.3550	M.3575	M.35100	M.4500	M.4525	M.4550	M.4575	M.45100
Compressive strength (MPa)	43.30	42.86	41.76	39.26	40.00	33.96	32.70	32.36	31.16	32.00

test. Temperature balance in construction site and lab must be constantly controlled as an important factor considerably affecting absorption of the specimens [5, 12]. Variations of water absorption in various mix designs vs. increasing the amount of recycled aggregates can be assessed through conducting the test, plotting the points of diagram, linear fitting of plotted points and calculating slope of the curve as absorption coefficient. The results of total water absorption and absorption coefficients of specimens are listed in Table 7.
According to the diagram in Figure 6, capillary water absorption coefficient increases in mix designs by enhancing water-cement ratio and the amount of recycled aggregates, indicating an increase in capillary water absorption and a decrease in durability of the concrete. Apparently, there is a slight increase in absorption while replacing recycled aggregates by 25%.

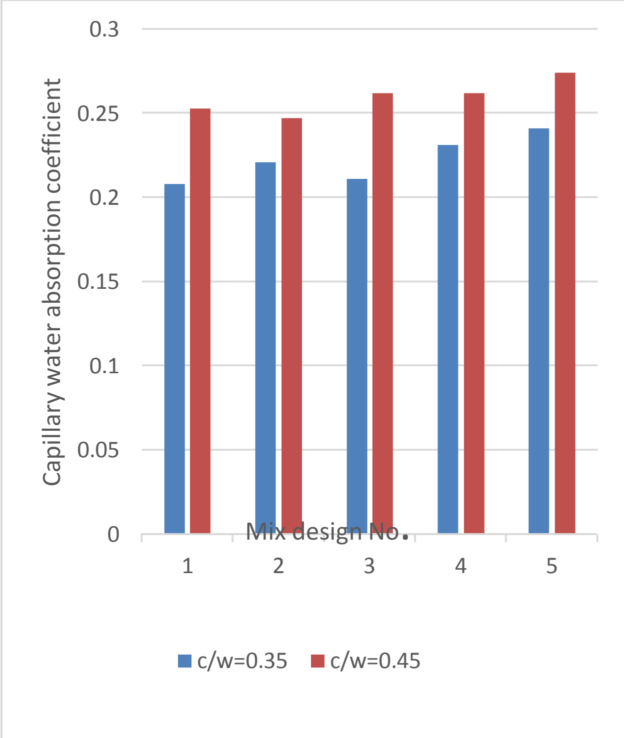

Figure 6. Diagram of variations of capillary water absorption coefficient in mix designs vs increasing the amount of recycled aggregates.

Table 7. Results of capillary water absorption test

mix design	M.3500	M.3525	M.3550	M.3575	M.35100	M.4500	M.4525	M.4550	M.4575	M.45100
Absorption coefficient of water	0.827	0.894	0.895	1.068	1.912	2.122	2.160	2.213	2.185	2.363
Total percentage of absorption	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52

- **Water penetration under pressure**

Permeability of concrete in under influence of numerous factors among which porosity of concrete, including porosity of aggregates and cement paste and their connection, is the most important; there are various experiments to specify the criterion, such as water penetration under pressure test which seeks to determine permeability and durability of concrete. The test is carried out on cube specimens of 15 cm × 15 cm × 15 cm, according to BS EN 12390. 28-day cured specimens are placed between clamps of testing machine and compressed 5 times under pressure of water for 72 hours. Rate and depth of water penetration is then measured when specimens are split in half by applying axial force. Table 8, The diagram of water penetration vs variations of recycled aggregates and W/C is plotted consequently [13]. Table 8 represents the results of water penetration under pressure including rate and depth of water penetration in different mix designs. According to the diagram in Figure 7, permeability enhances by increasing the amount of recycled aggregates. Moreover, blue columns represent mix designs with W/C of 0.35 and cement content of 500 Kg/m3 while orange columns demonstrate mix designs with mix designs with W/C of 0.45 and cement content of 450 Kg/m3. Significant differences between adjacent blue and orange columns indicate dramatic impact of water-cement ratio and cement content on permeability of concrete.

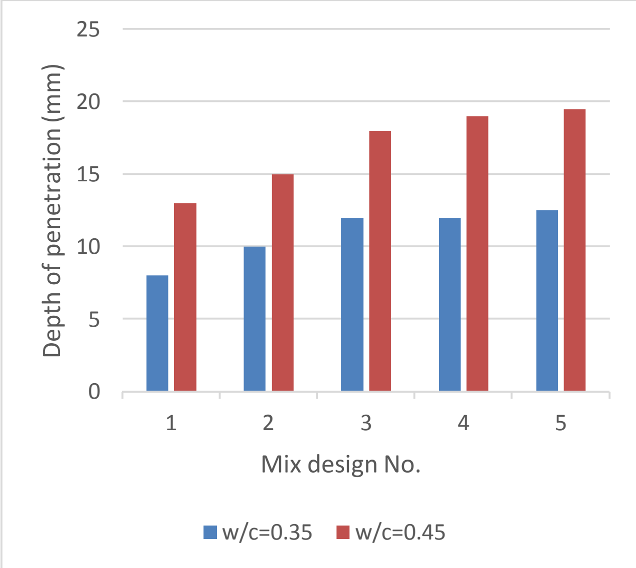

Figure 7. Diagram of variations of water penetration in mix designs vs amount of recycled aggregates

Table 8. Results of water penetration under pressure

mix design	M.3500	M.3525	M.3550	M.3575	M.35100	M.4500	M.4525	M.4550	M.4575	M.45100
Rate of water penetration (ml)	12	12	12	12	12	12	12	12	12	12
Average depth of penetration (mm)	8	8	8	8	8	8	8	8	8	8

- **summary and discussion**

As the result showed, increasing the amount of recycled aggregates clearly causes a decrease in compressive strength and an increase in permeability. In fact, criterion of strength has an inverse relationship with permeability; in other words, permeability falls as strength of concrete rises but rate of the variations varies due to multiple reasons.

The reasons may include good gradation of materials, filling the pores in concrete due to strong bond between cement paste and aggregates, less air voids in concrete, etc.; because penetration of external substances through concrete layers decreases as pores and air voids within concrete ingredients is reduced; and good gradation improves compressive strength of concrete so that plastic concrete completely fills pores in aggregates and provide a homogeneous mixture.

As illustrated in diagrams, the use of recycled aggregate has more significant influence on permeability than compressive strength of concrete. A numerical comparison between strength and permeability of control specimens – the specimens made of natural aggregates as well as the specimens with substitution of recycled aggregates by 100%- demonstrates that there is about a 10% decrease in compressive strength while depth of water penetration roughly increases by 50%.

4. Conclusion

- Following results were obtained in regard to the tests, used materials and research objectives:
- Compressive strength was dramatically reduced by increasing the amount of coarse recycled aggregate so that compressive strength of concrete specimens declined by 2-10% as the amount of recycled aggregate rose from 25% to 100%.
- Electrical resistance of specimens decreased by increasing the amount of recycled aggregate; so that according to the tests, electrical resistance was reduced by 5-20% on average as substitution by recycled aggregate increased from 25% to 100%. Thus, it was concluded that durability of concrete decreased by increasing the amount of recycled aggregate.
- Gradation of stone materials had a great impact on strength and durability of concrete so that the increase in amount of recycled aggregate and variation of coarse gradation in mix design with 100% recycled gravel caused a 2-3% growth in compressive strength compared to the mix design with 75% replacement. Therefore, a well-optimized gradation must be applied for mix design.
- Increasing the amount of recycled aggregates, based on the type and substance, caused segregation and bleeding in concrete so that superplasticizer had to be reduced; that may be because of fine cement particles in recycled aggregate and grading variation of the materials.
- Increasing the amount of recycled aggregates generally enhanced percentage of capillary water absorption; so that according to the results of tests, water absorption rose by 5-15% in specimens by increasing percentage of recycled aggregates, indicating an increase in permeability and a decrease in durability of concrete.
- Increasing the amount of recycled aggregates resulted in reduction of self-compacting concrete criteria like slump, J-ring, etc. which indicated decline of plasticity, workability, passing ability and so on and that might be because of grading variations.
- Generally, according to the results, this type of concrete could be a viable alternative to ordinary concrete; but due to its increased permeability, this type of concrete must be assessed in terms of the criterion in case of construction in areas where the concrete is exposed to penetrative substances, such as moist regions with carbonate pollutants, beaches, etc.

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