# Assessing Durability of Roller Compacted Concrete

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## ABSTRACT

Roller Compacted Concrete (RCC) is a technology characterized mainly by the use of rollers for compaction; this technology achieves significant time and cost savings in the construction of dams and roads. The primary scope of this research is to study the durability and performance of roller compacted concrete that was constructed in the laboratory using roller compactor manufactured in local market. A total of (60) slab specimen of (38×38×10) cm was constructed using the roller device, cured for 28 days, then 180 sawed cubes and 180 beams are obtained from RCC slab. Then, the specimens are subjected to 60 cycles of freezing and thawing, sulfate attack test and wetting and drying. The degree of effect of the type of coarse aggregate (crushed and rounded), cement type (OPC and SRPC) and cement content on the durability of RCC were investigated. The results indicated that RCC that contain SRPC has beneficial effects on properties of RCC as compared to RCC that contain OPC after durability testing. Based on the testing results, it was concluded that the resistance of RCC specimens to freezing and thawing, wetting and drying and sulfate attack test increase as cement content increase. The results also indicate that using RCC that contain crushed aggregate has a positive effect on the overall properties of RCC, as compared with RCC that contain rounded aggregate after durability testing.

**Keywords:** roller compacted concrete, durability, freezing and thawing, sulfate attack test, wetting and drying.

# تقييم ديمومة الخرسانة المرصوصة بالحدل

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## الخلاصة

تعتبر الخرسانة المرصوصة بالحدل من التقنيات التي تعتمد بالدرجة الأكبر خاصية إستعمال الحادلات لرص الخرسانة،هذه التقنية توفر وتحفظ الوقت المهم والكلفة في إنشاء السدود و الطرق. ان الهدف الرئيسي من هذا البحث هو دراسة ديمومة واداء الخرسانة المرصوصة بالحدل التي تم تصنيعها مختبريا بأستخدام جهاز حدل صنع في الاسواق المحلية. 0يتضمن الجزء العملي تحضير (60) بلاطة خرسانية مرصوصة بالحادلة بأبعاد (٣٨×٣٨×١٠) سم،بعد ذلك انضجت لمدة 28 يوم، ثم تم تقطيع هذه البلاطات الى (180) مكعب و (180)عتبة. تم تعريض النماذج الى 30و60 دوره من الانجماد والذوبان , فحص تأثير الكبريتات و الترطيب والتجفيف. تم دراسة نوع السمنت ( السمنت البورتلاندي الاعتيادي و السمنت المقاوم للكبريتات) وتأثير محتوى السمنت على ديمومة الخرسانة المرصوصة بالحادلة. من خلال النتائج التي تم الحصول عليها وجد ان مقاومة النماذج الحاويةعلى السمنت المقاوم للكبريتات له تأثير ايجابي على خواص الخرسانة المرصوصة بالحدل مقارنة مع النماذج الحاويةعلى السمنت البورتلاندي الاعتيادي بعد تعريض النماذج الى فحوصات الديمومة. اعتمادا على نتائج الفحوصات تم الاستنتاج ايضا بأن مقاومة نماذج الخرسانة المرصوصة بالحدل لدورات الانجماد والذوبان , الترطيب و التجفيف و فحص مقاومة تأثير الكبريتات تزداد بزيادة محتوى السمنت .

# 1. INTRODUCTION

The American Concrete Institute (ACI) defines RCC as “concrete compacted by roller compaction; in its unhardened state, will support a roller while being compacted.” Properties of hardened RCC can be similar to those of conventionally placed concrete. The term “roller compaction” is also defined by ACI as “a process for compacting concrete using a roller, often a vibrating roller. **USACE , 2000.**

**Kreuer ,2006,** defined Roller Compacted Concrete as a dry concrete consisting of more aggregate and less cement paste than conventional concrete. Because cement is the most expensive constituent of concrete, RCC is less expensive in terms of cost of materials.

Due to its dry nature, RCC has a zero slump and it is placed without forms or finishing. RCC pavements do not require joints, dowels, or reinforcing steel. Relatively large quantities of RCC pavement can be placed rapidly with minimal labor and equipment, enabling speedy completion of tightly scheduled pavements.

RCC is used for the construction of dams and pavements, **Chun et al , 2008**. RCC first was used to build dams. Besides the reduced construction cost resulting mainly from labor and equipment savings, its principal advantage for mass construction is the low cement content of the mixture which greatly reduces problems due to the heat of hydration of cement, **PCA , 2004.**

RCC pavement is much stronger and durable than asphalt pavement. RCC will not rut from high axle loads, or shove or tear from turning or braking of operating equipment. It will not soften from heat generated by hot summer sun or material stored on RCC floors. RCC resists degradation from materials such as diesel fuel, **Naik et al , 2001**.

The primary differences in proportions of RCC pavement mixtures and conventional concrete pavement mixtures are, **ACI 325-10R-, 1995.**

- RCC is generally not air-entrained;
- RCC has lower water content;
- RCC has lower cement paste content;
- RCC generally requires a larger amount of fine aggregate in order to produce a combined aggregate that is well-graded and stable under the action of a vibratory roller. RCC pavements, like all other types of concrete elements, can be subjected to many types of deterioration such as abrasion/erosion, freezing and thawing, wetting and drying, and other factors such as alkali-silica reaction, and sulfate attack. RCC is now increasingly used for the construction of pavements exposed to very severe loading and environmental conditions, **PCA , 2004**.

RCC is not just more economical than the currently used pavement alternatives, but has also shown high durability and early gain of mechanical strength in both the field and the laboratory, **Kreuer 2006**.

RCC has been used in Iraq in mid-eighties below the foundations of the medical drug factory near Mosul and also in the AL-Adaim Dam, **Ahmed , 2001**. Another reported use was in the construction of extra lane for Mosul- Duhok highway in 1988, **Sarsam , 2002**.

## 1.1 Objective of the Study

The objective of this research is to assess durability and performance of a test slab that was constructed by using roller compactor machine. The main aims of this study are as follows:

1- Studying degree of effect of freezing and thawing cycles, wetting and drying cycles and sulfate attack on the modulus of rupture of RCC slabs.
2- Investigating degree of effect of cement type and cement content on the performance of RCC slabs during durability testing.

# 2 . EXPERIMENTAL WORK

## 2.1 Material Characteristics

### 2.1.1 Cement

Both ordinary Portland cement (OPC) and sulfate resisting Portland cement (SRPC) manufactured in Iraq with a commercial name of (Tasluga, Al-jesser) is used for RCC mixes throughout the present work.

### 2.1.2 Aggregate

Crushed gravel with a nominal size of (19 mm) brought from Nibaai region is used in this work. The aggregate is washed and cleaned by water. Later, it is air dried and separated into different sizes. Fine aggregate (passing sieve No.4 BS.) brought from Al-Ukhaider region are used in this work. The sand is washed and cleaned by water. Later, it is air dried and separated into different sizes.

### 2.1.2.1 Gradation of Coarse and Fine Aggregate

Dense gradation usually used for asphalt concrete pavement in Iraq has been adopted for this investigation. The coarse and fine aggregates are sieved to different sizes; the desired weight of each size of aggregate is taken and combined to satisfy the requirements of gradation**.** The design over all gradation of aggregate is selected by using of State Commission of Roads and Bridges **SCRB , 2004.** The grain size distribution is illustrated in **Table 1.**

### 2.1.3 Water

The water used in RCC mixes was drinking water of Baghdad area. This water was also used for curing**.**

### 2.2 Mix Design and Proportions of RCC Samples

The concrete mix is designed according to previous experience **Abdullah , 2011.** .Three different percentages of cement content has been selected (10 %, 12 %, and16 %) by weight of air dried aggregate and three different percentages of moisture content are used. The details of dry density at different moisture and cement contents are summarized in **Table 2**. Four types of mixes are adopted with three percentages of cement and

three percentages of moisture content for each mix; the types of mixes are as following:

1- Crushed aggregate + Natural sand + Ordinary Portland cement
2- Crushed Aggregate + Natural Sand + Sulfate resisting Portland cement.

### 2.3 Casting of RCC Slab Samples

### 2.3.1 The Molds

The steel molds manufactured in local workshop are used in this investigation. It consists of four sides made from angle section steel of (100×100×10 mm) with steel plate of (650×600×10 mm)**,** the sides and plate are connected together by bolts and two handles are welded with the plate to easy lift the mold and put on the vibrating table, the total weight of one mold is 51kg. A slab specimen having size of (380×380×100mm) is obtained from this mold. Molds details of slab specimens are shown in **Fig.1**.

### 2.3.2 The Roller Device

The device consists of a steel roller of 160mm diameter, 330 mm in length and 15 kg in weight is fixed by two bolts with device ,steel box of (600 ×460×180) mm is used to add various standard weights up to 138kg for applying loads on the roller to simulate the field conditions ,this box is connected by welding above the device, and two small wheels connected in the back direction for easy transporting the device during the work and two hands support is welded in the back of the device to easing push the device during the rolling as shown in **Fig.2** The total weight of this apparatus is 36 Kg.

### 2.3.3 Mixing

Before mixing the materials molds are prepared by cleaning, and their internal surfaces are covered by using nylon sheets to prevent loss of the water or material from sides during the rolling and to prevent adhesion with concrete after

hardening, after that for two minutes the cement and aggregate are dried mixed by hand mixing then a hole is formed at the mixture in the middle .Then required amount of water is poured and mixed for five to six minutes to achieve homogeneous mixture.

### 2.3.4 Compaction

#### 2.3.4.1 Compaction by vibrating table

The mixture is placed in the mold and subjected to initial compaction on a vibrating table for 3 layers of 30 seconds time interval.

#### 2.3.4.2 Compaction by using a roller device:

The mold is fixed in front of the roller compactor device and subjected to three stages of rolling based on the work done by **Sarsam ,2002. Abdullah ,2011.** and **Abdulrahim ,2011.** for each stage10 passes is applied .This number of passes is suitable to achieve the good rolling with low labor , and the rolling action is taken in x-x direction , then the same sequence have been repeated in the y- y direction as shown in the **Fig.3** . This is to insure the compaction of the slab sides. The first stage represent the initial compaction in the field, a total load of 1.1 kg/cm width (by using roller compactor weight only) is applied with 10 passes of the roller in each direction. The concrete is settled in a level position and completely fill the slab mold and gives a level surface, the compaction by using a roller device is shown in **Fig.4**.

The second stage may simulate the intermediate field compaction; a total load of 3.2 kg/cm width (by using 6 standard loads each load of 11.5 kg plus roller compactor weight) is applied with 10 passes of the roller in each direction. The final stage represents the finishing compaction in the field a total load of 5.3kg/cm width (by using 12 standard loads each load of 11.5 kg plus roller compactor weight) is applied with 10 passes of the roller in each direction.

### 2.3.5 Curing

After molding and finishing the compaction, the surface of casted samples is leveled by hand trawling and covered with polyethylene sheet to prevent evaporation of moisture from the fresh concrete, and left in lab

at room temperature of 30±5˚c to next day for setting then, the samples are taken out of the molds. Then, the specimens are immersed in the curing tank for (28) days at 30±5˚c. Part of RCC slab specimens after 28 day curing is shown in **Fig. 5**.

### 2.3.6 Cutting of RCC slab specimens

By using the procedure of **ASTM C42/C42M-(2003)** sawed cubes and beams are obtained from RCC slab specimens, a total of 180 cubes of (100×100×100 mm) are obtained from slab specimens, and 180 beams of (380×80×100mm) are also obtained from slabs specimens. Samples obtained from RCC slab is shown in **Fig. 6**.

## 2.4 Durability Investigations

### 2.4.1 Freezing and thawing test

The freezing and thawing test is carried out according to ASTM C-666-(2002) procedure B, (rapid freezing in air and thawing in water). Freezing and thawing tests are started by placing the specimens (4 cubes and 4 beams from each mixes) in the thawing water at the beginning of the thawing phase of the cycle at temperature 30 ± 3 ◦ C for 2 ½ hr to ensure that the specimens are completely thawed then, the specimens are taken out of water and are placed in deep freezer at temperature ( -11± 1◦ C) for 4 ± ½ hr as the beginning of the freezing phase of the cycle. This procedure is repeated for 60 cycles of freezing and thawing**.**

### 2.4.2 Sulfate attack test

Resistance of RCC specimens to disintegrate by saturated solution of sodium sulfate is determined according to ASTM C –88 (1999).

### 2.4.3 Wetting and drying cycles

The RCC specimens are subjected to cycles of wetting and drying in the light of many research works **Mahmoud ,1977. AL-Delaimee , 1989. Ahmed, 2001, and Riyadh , 2005.** The cycles are started by placing the specimens (4 cubes and 4 beams from each mixture) in the oven at temperature 70 ◦ C for 24 hr. Then, it is removed from oven and it is immersed in water for 24 hr at

28 ◦ C .The alternate immersion and drying of specimens are repeated for 60 cycles.

## 2.5 Modulus of Rupture Test

The modulus of rupture is determined by using sawed beams of sizes (380×100×80) mm according to **ASTM C293-(2003).**

## 3. ANALYSIS AND DISCUSSION OF TEST RESULTS

### 3.1 Effect of Type of Cement and Cement Content on Modulus of Rupture of RCC during Freezing and Thawing Cyclic

Modulus of rupture of RCC that made of sulfate resisting Portland cement shows higher values than that RCC made of ordinary Portland cement before and after subjected to freezing and thawing cycles as shown in **Table 3**.

When testing beam specimen with 16% sulfate resisting Portland cement at 60 cycles of freezing and thawing the modulus of rupture is higher than that of specimens that have ordinary Portland cement by 14.285% as shown in **Fig.7**.This happens because the strength is developed rapidly for finer cement since the rate of hydration depends on the fineness of cement particles, where the surface area of cement represents the material available for hydration. This affects the resistance of cement paste and amount of water that able to freeze in it.

It can be seen that the modulus of rupture of sawed beams which obtained from RCC slab samples increases with increasing cement content. Specimens tested after 60 cycles of freezing and thawing shows increasing in modulus of rupture as cement content increase, the range of this increase is (22.43 -11.36%) for (OPC) **.**This may be attributed to the cement availability for hydration filling the voids, this will give better permeability and create stronger bonds within the concrete matrix and thus provide more resistance to frost damage in concrete were based up on the expansion of ice upon freezing and the subsequent stress , This agrees with **stutzman , 1999.** The durability can be improved by increasing cement content, Balaguru **and Ramakrishnan , 1986.**

**Table 4** shows percentage of decrease in modulus of rupture of RCC that subjected to alternate freezing and thawing cycles, while **Fig. 8** shows the relationship between percentages of decrease in modulus of rupture with cement content for RCC made of OPC and SRPC**.**

The result also shows that the modulus of rupture of RCC decreases as the cycles increase. It can be seen from **Table 4** that the modulus of rupture at 60 cycles for beam specimens with 10% ordinary Portland cement shows maximum reduction of 12.213% , while beam specimens with 10% sulfate resisting Portland cement shows maximum reduction at 60 cycles of 6.619% . The reason of decreasing in strength is internal damage result from freezing and thawing cycles causes microscopic cracks in the cement paste leading to change in mechanical parameters of the concrete. This agrees with **Petersen , 2007.**

### 3.2 Effect of Type of Cement and Cement Content on Modulus of Rupture of RCC during Wetting and Drying Cyclic

It is clear from the test results that the modulus of rupture of RCC made of SRPC cement is higher than that OPC before and after subjecting specimens to cycles of wetting and drying as shown in **Table 5** .

When 16% sulfate resisting Portland cement is used the results show modulus of rupture higher than that ordinary Portland cement by 14.602% at 60 cycles of wetting and drying. This may be attributed to that

the rate of hydration will be reduced at each drying period for ordinary and sulfate resisting Portland cement but the strength of sulfate resisting Portland cement still developed faster than that ordinary Portland cement because SRPC is finer than OPC and the rate of hydration depends on the fineness of cement particles. **Fig. 9** shows the relationship between modulus of rupture and number of cycles for RCC made of ordinary and sulfate resisting Portland cement.

From the results in **Table 5**, it can clearly be seen that the modulus of rupture increases with increasing cement content before and after cycles of wetting and drying. The percentage of increasing in modulus of rupture is 21.815% when ordinary Portland cement content changes from 10% to 12% and 9.885% increasing in modulus of rupture when cement content changes from 12% to 16%. This trend may be attributed to higher cement content created stronger bonds within the concrete matrix and this provide more resistance to microcracks that result from drying process.

**Table 6** shows percentage of decrease in modulus of rupture of RCC that subjected to wetting and drying cycles, **Fig.10** shows the relationship between percentage of decrease in modulus of rupture with cement content for RCC made of OPC and SRPC.

It can be seen that the modulus of rupture decrease as the cycles increase. The percentage of decrease in modulus of rupture at 30 and 60 cycles for RCC made of 12% ordinary Portland cement is 4.545% and 9.350% respectively than modulus of rupture at zero cycle, and the percentage of decrease in modulus of rupture at 30 and 60 cycles for RCC made of 12% sulphate resisting Portland cement is 3.899% and 8.050% respectively than modulus of rupture at no cycle. The reduction in strength is due to induces microcracks in RCC material and the rate of hydration will be reduced at each drying period.

### 3.3 Effect of Type of Cement and Cement Content on Modulus of Rupture of RCC during Sulfate Attack Cyclic

It is clear from the test results that modulus of rupture of RCC made of SRPC is higher than that RCC made of OPC before and after subjecting 60 cycles of wetting in sodium sulfate solution and drying as shown in **Table 7** . RCC made of 16% SRPC shows modulus of rupture higher than RCC made of OPC by 17.227% at 60 cycles .This is because sulfate resisting Portland cement have lower content of $C_3A$ that react with sulfate ion and form ettringite. **Fig. 11** shows the relationship between modulus of rupture and number of cycles for RCC made of ordinary and sulfate resisting Portland cement.

It is clear from the test result that the modulus of rupture before and after 30 and 60 cycles of wetting in sulfate solution and drying increase as cement content increase , specimens tested after 30 cycles and that content 12% and 16% OPC shows increasing in modulus of rupture as compared to reference RCC mix at 10% by 19.7% and 30.4% respectively ,and specimens tested after 60 cycles and that content 12% and 16% SRPC shows increasing in modulus of rupture as compared to reference RCC mix at 10% by 21.26% and 33.8% respectively. This happens because at high cement content the concrete is higher density than that low cement content and this leads to make the concrete less permeability and the resistance of concrete to sulfate attack is depended on its permeability, **Neville , 1995.**

It can be seen from **Table 8** that after 30 and 60 cycles of immersion in sodium sulfate solution and drying RCC made of 12% ordinary Portland cement shows percentage of decrease in modulus of rupture by 6.103% and 12.597 % respectively than that modulus of rupture at no cycles, and specimens which have 12% sulfate resisting Portland cement shows after 30 and 60 cycles of immersion and drying percentage of decrease in modulus of rupture by 4.150% and 7.924% respectively than that modulus of rupture at zero cycles. The reduction in modulus of rupture can be attributed to the same reasons of decrease in compressive strength. Fig. 12 shows the relationship between percentage of decrease in modulus of rupture with cement content for RCC made of OPC and SRPC.

## 4. CONCLUSIONS

1- The modulus of rupture RCC mixes decrease with the increase in freezing and thawing cycles, alternating wetting and drying cycles, and with increasing the number of immersion cycles in sodium sulfate solution and then drying.
2- The resistance of RCC to freezing and thawing cycles, wetting and drying cycles and sulfate attack test increases with increasing cement content.
3- RCC made of sulfate resisting Portland cement gave better durability than RCC made of ordinary Portland cement when subjecting the specimens to 60 cycles of freezing and thawing. Modulus of rupture was higher for samples containing sulfate-resisting cement, as compared with ordinary Portland cement by 14.285% at 16% cement content.
4- Resistance of RCC mixes to sulfate attack test cycles was improved when using Sulfate resisting Portland cement as compared with the ordinary Portland cement, the modulus of rupture of samples exposed for 60 cycles and containing Sulfate resisting cement is higher than the resistance of samples containing ordinary Portland cement by 17.227% at 16% cement content.
5- Resistance of RCC containing sulfate-resisting cement is better than specimens containing ordinary Portland cement when exposed to cycles of wetting and drying. The increase in the

modulus of rupture of the samples containing Sulfate resisting cement when exposed to 60 cycles of wetting and drying is 14.602% at 16% cement content.

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## List of Abbreviations

**$Mc_1$** Crushed Aggregate + Sand + 10% OPC
**$Mc_2$** Crushed Aggregate + Sand + 12% OPC
**$Mc_3$** Crushed Aggregate + Sand + 16% OPC
**$Mcr_1$** Crushed Aggregate + Sand + 10% SRPC
**$Mcr_2$** Crushed Aggregate + Sand + 12% SRPC
**$Mcr_3$** Crushed Aggregate + Sand +16% SRPC

**Table 1.** Grain size distributed used for RCC.

| Sieve Size (mm) | % Passing by Weight |
|---|---|
| 19 | 98 |
| 12.5 | 85 |
| 9.5 | 76.5 |
| 4.75 | 62.5 |
| 0.6 | 26.5 |
| 0.075 | 9 |

**Table 2.** Details of the design mixes of RCC Samples,Abdullah, 2011.

| Moisture content % | Dry Density ( gm. / cm$^3$ ) | | | | |
|---|---|---|---|---|---|
| | Cement content % | | | | |
| | **10** | **12** | **14** | **16** | **18** |
| 4 | 2.167 | - | - | - | - |
| 5 | 2.240 | 2.270 | 2.290 | - | - |
| 6 | 2.270 | **2.390** | 2.320 | - | - |
| 7 | **2.330** | 2.350 | 2.355 | 2.268 | 2.360 |
| 8 | 2.310 | 2.330 | 2.346 | **2.272** | 2.370 |
| 9 | 2.268 | 2.300 | 2.320 | 2.260 | 2.320 |
| 10 | - | - | 2.290 | 2.240 | - |
| 11 | - | - | - | 2.190 | - |

**Table 3.** Modulus of rupture of freezing and thawing cycles for RCC made of (OPC) and (SRPC).

| Mix Symbol | Modulus of Rupture (MPa) | | |
|---|---|---|---|
| | Number of freezing and thawing cycles | | |
| | **No cycle** | **30 cycles** | **60 cycles** |
| $Mc_1$ | 6.55 | 6.16 | 5.75 |
| $Mc_2$ | 7.7 | 7.41 | 7.04 |
| $Mc_3$ | 8.31 | 8.1 | 7.84 |
| $Mcr_1$ | 7.1 | 6.88 | 6.63 |
| Mcr2 | 7.95 | 7.72 | 7.43 |
| Mcr3 | 9.3 | 9.2 | 8.96 |

**Table 4.** Modulus of rupture after alternate freezing and thawing cycles for RCC made of (OPC) and (SRPC).

| Mix Symbol | Modulus of Rupture (MPa) | | |
|---|---|---|---|
| | Number of wetting and drying cycles | | |
| | No cycles | 30 Cycles | 60 Cycles |
| $Mc_1$ | 6.55 | 6.15 | 5.73 |
| $Mc_2$ | 7.7 | 7.35 | 6.98 |
| $Mc_3$ | 8.31 | 8 | 7.67 |
| $Mcr_1$ | 7.1 | 6.73 | 6.37 |
| Mcr2 | 7.95 | 7.64 | 7.31 |
| Mcr3 | 9.3 | 9.05 | 8.79 |

**Table 5.** Modulus of rupture of wetting and drying cycles for RCC made of (OPC) and (SRPC).

| Mix symbol | Percent decrease after 30 cycles | Percent decrease after 60 cycles |
|---|---|---|
| $Mc_1$ | 6.1 | 12.5 |
| $Mc_2$ | 4.5 | 9.3 |
| $Mc_3$ | 3.7 | 7.7 |
| $Mcr_1$ | 5.2 | 10.2 |
| Mcr2 | 3.8 | 8.0 |
| Mcr3 | 2.6 | 5.4 |

**Table 6**. Modulus of rupture after alternate wetting and drying cycles for RCC made of (OPC) and (SRPC).

| Mix symbol | Percent decrease after 30 cycles | Percent decrease after 60 cycles |
|---|---|---|
| $Mc_1$ | 5.9 | 12.2 |
| $Mc_2$ | 3.7 | 8.5 |
| $Mc_3$ | 2.5 | 5.6 |
| $Mcr_1$ | 3.0 | 6.6 |
| Mcr2 | 2.8 | 6.5 |
| Mcr3 | 1.0 | 3.6 |

**Table 7.** Modulus of rupture of sulfate attack test for RCC made of (OPC) and (SRPC).

| Mix symbol | Percent decrease after 30 cycles | Percent decrease after 60cycles |
|---|---|---|
| $Mc_1$ | 7.7 | 15.2 |
| $Mc_2$ | 6.1 | 12.5 |
| $Mc_3$ | 5.1 | 10.5 |
| $Mcr_1$ | 5.7 | 11.6 |
| Mcr2 | 4.1 | 7.9 |
| Mcr3 | 3.0 | 6.3 |

**Table 8.** Modulus of rupture after sulfate attack test for RCC made of (OPC) and (SRPC).

| Mix Symbol | Modulus of Rupture (MPa) | | |
|---|---|---|---|
| | Number of freezing and thawing cycles | | |
| | No cycle | 30 cycles | 60 cycles |
| $Mc_1$ | 6.55 | 6.16 | 5.75 |
| $Mc_2$ | 7.7 | 7.41 | 7.04 |
| $Mc_3$ | 8.31 | 8.1 | 7.84 |
| $Mcr_1$ | 7.1 | 6.88 | 6.63 |
| Mcr2 | 7.95 | 7.72 | 7.43 |
| Mcr3 | 9.3 | 9.2 | 8.96 |

**Figure1.** RCC mold .

**Figure 2.** The roller device.

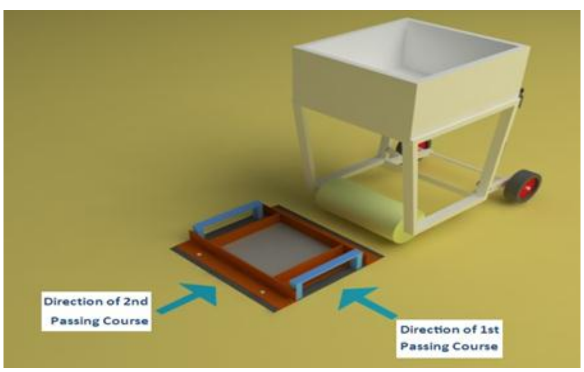


**Figure 3.** The rolling directions.

**Figure 4.** The compaction with a roller device.

**Figure 5.** Part of RCC slab specimens.

**Figure 6.** Part of samples obtained from RCC slab.

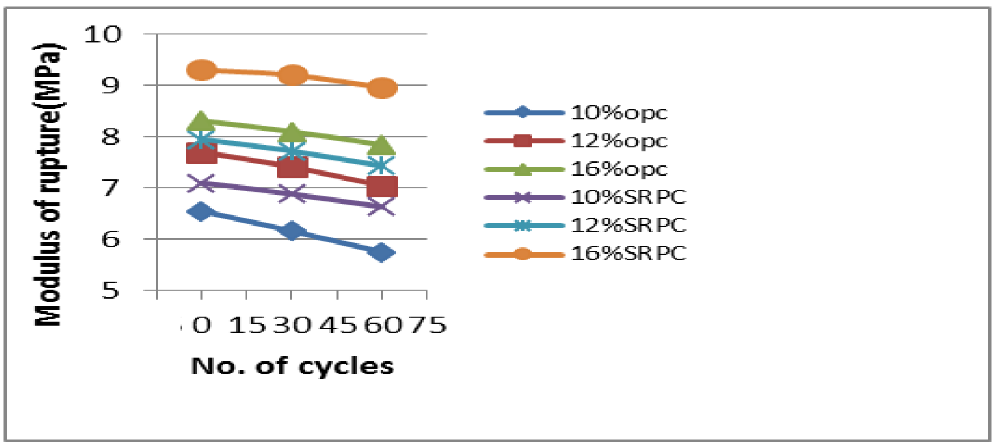


**Figure 7 .** Variation in modulus of rupture with No. of cycle after freezing and thawing for RCC made of (OPC) and (SRPC).

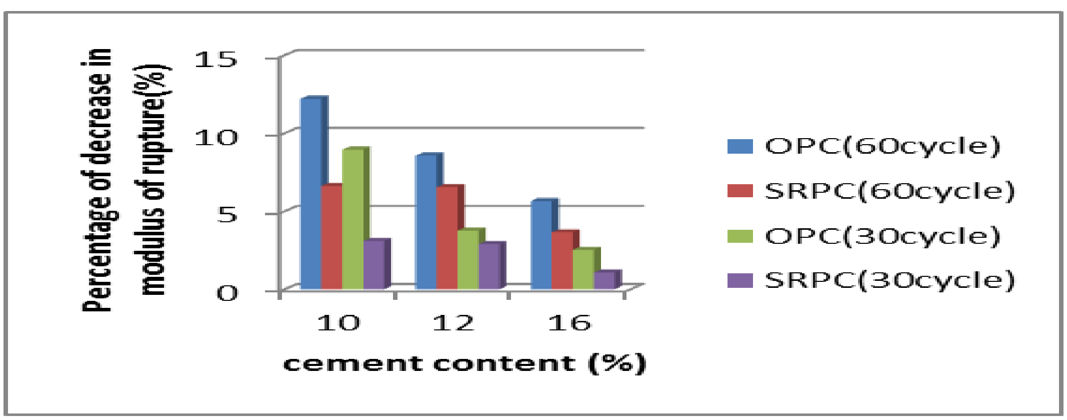


**Figure 8.** percentage of decrease in modulus of rupture with cement content for RCC made of(OPC) and (SRPC) after freezing and thawing cycles.

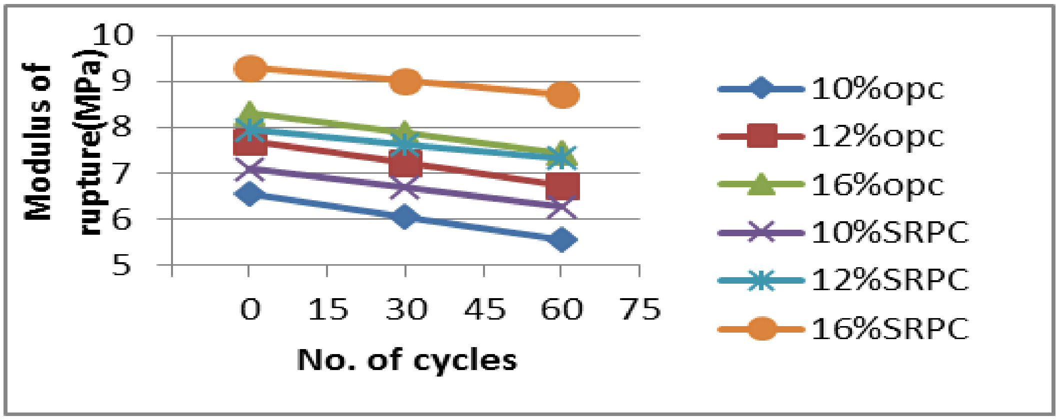


**Figure 9**. Variation in modulus of rupture with No. of cycle after wetting and drying for RCC made of (OPC) and (SRPC).

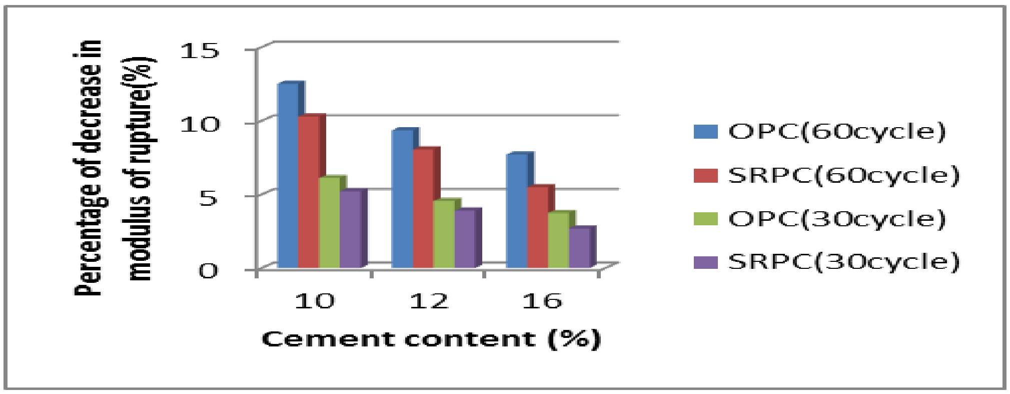


**Figure 10.** percentage of decrease in modulus of rupture with cement content for RCC made of (OPC) and (SRPC) after wetting and drying cycles.

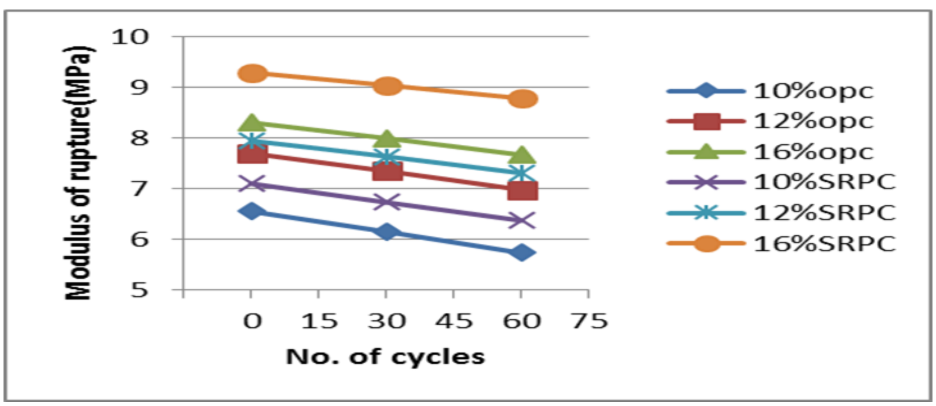


**Figure 11.** Variation in modulus of rupture with No. of cycle after sulfate attack test for RCC made of (OPC) and (SRPC).

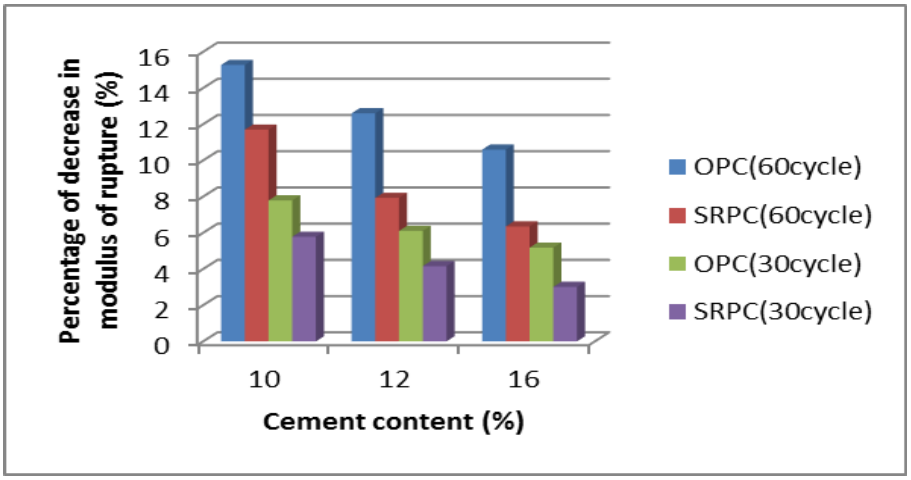


**Figure 12 .** percentage of decrease in modulus of rupture with cement content for RCC made of (OPC) and (SRPC) after sulfate attack test.