

## **Effect of Drying-Rewetting on Elastic Modulus of Portland Cement Paste and Mortar**

**Jamal A. Al-Mudaiheem**

*Department of Civil Engineering, King Saud University,*

*P.O. Box 800, Riyadh-11421, Saudi Arabia*

**Abstract.** The effect of drying and rewetting on the dynamic elastic modulus of 0.4 and 0.6 W/C ratio pastes and mortar were investigated. Drying results in a significant reduction in the dynamic elastic modulus due to the moisture stress gradients. The original undried value of the dynamic elastic modulus is totally recovered upon subsequent rewetting of the dried specimen. It is concluded that effects such as microcracking caused by drying can be avoided. Therefore, miniature specimens may be used to measure the unrestrained response of cement paste and concrete. The study shows that the reduction in the dynamic elastic modulus increases with increasing aggregate content and decreases with increasing W/C ratio.

### **1. Introduction**

Internal stress gradients are created during the drying process of hardened cement paste. The stresses are believed to be large enough to affect the observed deformation [1]. It was concluded [2] that the drying shrinkage of cement paste is not a material parameter because of microcracks formed by those stresses.

Microcracking is claimed to be created during drying even at high relative humidities (RH) [3]. This was explained by the differences of contraction and rigidity between dense calcium hydroxide crystals and porous C-S -H\* gel which causes a local residual stresses around and within the calcium hydroxide particles. The fact that the permeability coefficient of a dried paste was found to be 70-fold greater than that of undried paste [4] has been interpreted by some researchers [2,5] to be the effect of microcracking.

It has been anticipated that the variation in the properties of concrete upon drying and rewetting may be explained by a detailed examination of the modulus of elasticity of the concrete system under varying hygral states [6].

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\*Standard cement nomenclature is used: C = CaO, S = SiO<sub>2</sub> and H = H<sub>2</sub>O

Dynamic elastic modulus measurements are comparatively easier to perform than static modulus measurements. The dynamic elastic modulus measurement is a non-destructive test; therefore, it is specially suitable since the effects of cyclic changes in humidity on the modulus are to be evaluated. Radjy and Richards [7] have reported that the dynamic elastic modulus decreases as the hydrated cement paste specimen loses water.

In an attempt to supplement and tie together existing data the investigation reported herein was conducted to determine the dynamic elastic modulus values and weight changes of Portland cement paste and mortar specimens dried at different relative humidities and at different rates. Subsequently, these specimens were rewetted, and the dynamic elastic modulus as well as the weight changes were monitored.

## 2. Materials and Methods

Pastes of Type I Portland cement were cast in slabs. The W/C ratios used were 0.4 and 0.6. Mortar specimens of 0.4 and 0.6 W/C ratios containing 20, 30, 40 and 50% Ottawa sand by overall volume were also cast in slabs. Ottawa sand was graded according to ASTM C109. To avoid sedimentation, the pastes were rotated in sealed plexiglass molds until they had set. The 0.6 W/C ratio paste was rotated in sealed containers and allowed to partially hydrate in a horizontal drum rotating at 10 rpm for 6 hours prior to casting to minimize loss of mixing water from the mold. The blocks ( $2 \times 11 \times 11$  cm) of hardened pastes and mortar were demolded and cured in an air tight container with deionized water saturated with lime. The paste and mortar slabs were allowed to hydrate for 240 days at room temperature of  $74 \pm 3^\circ\text{F}$  ( $23 \pm 2^\circ\text{C}$ ). At the end of the curing period thin specimens ( $2.5 \times 10 \times 75$ mm) were cut from the slabs using a diamond saw.

## 3. Specimen Testing

The specimens were dried in desiccators conditioned at 50% and 0% RH using aqueous solutions of sulfuric acid. The RH was maintained by stirring the solution continuously during the entire period of drying. Zero percent RH corresponds to drying over the vapor pressure of concentrated sulphuric acid. The temperature of the room was kept at  $74 \pm 1^\circ\text{F}$  ( $23 \pm 1^\circ\text{C}$ ).

Dynamic elastic modulus measurements were performed on moisture cured, desiccated and rewetted specimens. Resonant frequency values were determined on the samples in accordance with ASTM-C215 to calculate the dynamic elastic modulus. The test was performed inside the desiccator to minimize the effect of changing RH.

At least three measurements of each resonance frequency were made, the precision was about  $\pm 5$  cycles per sec. per 1000 cycles per second. Resonance frequencies ranged from about 700 to 1500 cycles per sec.

The dynamic elastic moduli were determined from the fundamental resonance frequencies in flexure. The method is described by Pickett [8] and Spinner and Teftt

[9]. The following equation for the flexural vibration of prisms which was developed by Pickett [8] was used to calculate the dynamic elastic modulus:

$$E = 2.47 \times 10^{-3} \frac{W l^3 f_f^2}{a^3 b}$$

where

- E is the dynamic elastic modulus (psi)
- W is the specimen weight (lb)
- l is the specimen length (in)
- a is the specimen thickness (in)
- b is the specimen width (in)
- f is the fundamental resonant frequency (Hz)

The specimens were supported near the nodal points, which occur at 0.224 l from each end for the first mode. Thin wire clips were used to support the specimen in order to minimize restraints.

#### 4. Results

The changes in dynamic elastic modulus for the 0.4 and 0.6 W/C ratios pastes dried at 50% RH for 2 days and then rewetted are shown in Fig. 1. The changes in dynamic elastic modulus of other paste samples of the same W/C ratios dried at 0% RH for 1 day and then rewetted in steps are shown in Fig. 2.

Dynamic elastic modulus versus drying-rewetting time curves are shown in Figs. 3 and 4 for 0.4 and 0.6 W/C ratios paste and mortar samples containing 20, 30, 40 and 50% Ottawa sand by overall volume. The samples were dried at 50% RH for 40 days and then rewetted. In Figs. 5 and 6 the changes in dynamic elastic modulus of other samples of the same series dried at 0% RH for about 80 days and then rewetted are shown.

Also shown in Figs. 1 to 6 are concomitant weight change curves for the specimens investigated. Each point reported is the average of two specimens. No major variations were encountered between the two companion specimens.

The shapes of the curves are typical in that a considerable part of the loss in dynamic elastic modulus takes place at early ages of drying, which is associated with a considerable amount of water loss. The shapes of the dynamic elastic modulus curves are in general agreement with those reported by other investigators [6, 10].

Figures 1-6 show that the decrease in dynamic elastic modulus caused by drying is a completely reversible process or even more. The original value of the dynamic modulus is totally recoverable through subsequent saturation of the cement paste and mortar samples. The improvement in dynamic elastic moduli of some series

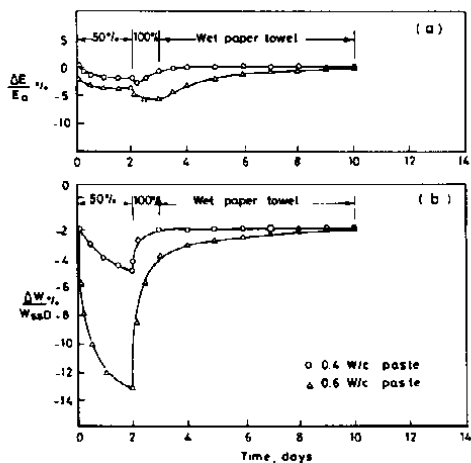


Fig. 1. Effect of drying at 50% and rewetting on (a) dynamic elastic modulus with time (b) weight change with time

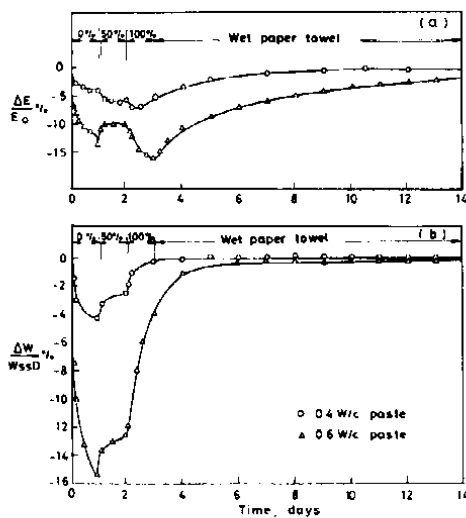


Fig. 2. Effect of drying at 0% and subsequent rewetting on (a) dynamic elastic modulus, (b) weight change with time

Fig. 3. Changes of dynamic elastic modulus and weight of 0.4 w/c ratio paste and mortar upon drying at 50% RH and rewetting.

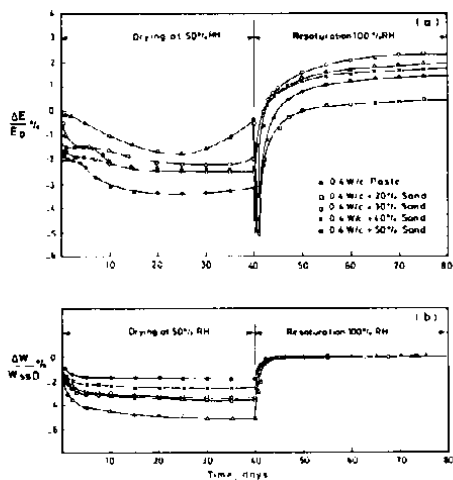
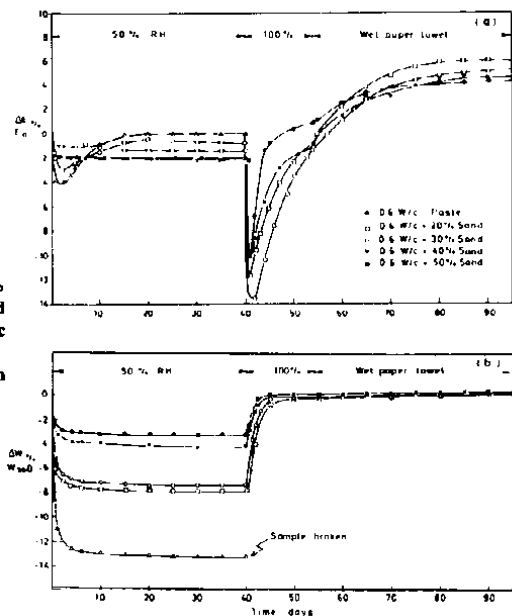
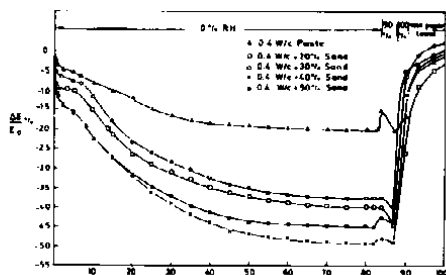


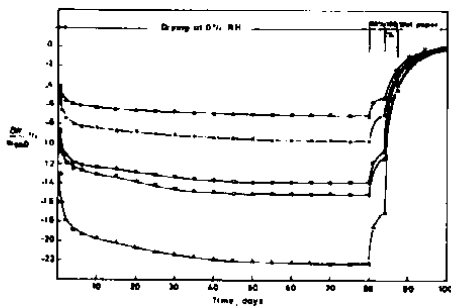
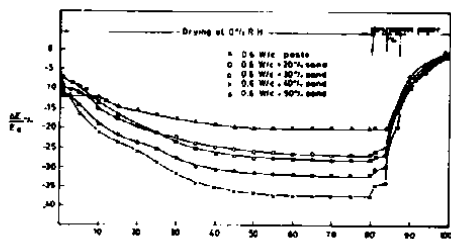
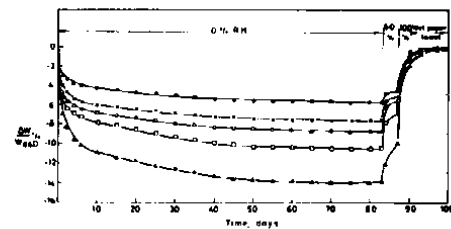
Fig. 4. Effect of drying at 50% RH and ratio paste and mortar on (a) dynamic elastic modulus, (b) weight change with time.



**Fig. 5.** Changes in dynamic elastic modulus and weight of 0.4 w/c paste and mortar due to drying at 0% RH and subsequent rewetting.



**Fig. 6.** Changes in dynamic elastic modulus and weight of 0.6 w/c paste and mortar due to drying at 0% RH and subsequent rewetting.



upon subsequent saturation is not significantly high, therefore, no explanation is available until further clarification is acquired.

## 5. Discussion

### 5.1. Dynamic Elastic Modulus-Weight Loss Curves

The dynamic elastic modulus versus weight loss curves for the 0.4 and 0.6 W/C ratios pastes dried at 50% and 0% RH for about 2 days are shown in Fig. 7. The two different paste mixes studied have a unique curve upon drying at each RH. The curves were constructed from concomitant dynamic elastic modulus and weight change values from Figs 1 and 2. Figures 8 and 9 include the relationship between changes in dynamic elastic modulus and weight loss for the 0.4 and 0.6 w/c ratio pastes and mortar dried at 0% RH. It should be noted that the weight changes of the mortar specimens were normalized to the weight of the paste. The curves show complete overlap for the various paste and mortar specimens. This suggests that the change in dynamic elastic modulus is closely related to the change in water during drying. Thus, the change in dynamic elastic modulus is attributed to the moisture movement throughout the samples. This is in agreement with findings by other investigators [11, 12]. The moisture movement is associated with a moisture stress gradient that causes the drop in the elastic modulus. Moisture stress gradients are also developed at the beginning of the rewetting process; therefore there should be a further drop in the dynamic elastic modulus at the early stages of rewetting as can be seen in Figs. 1 through 6. The dynamic elastic modulus started a gradual increase back to the original undried modulus upon subsequent rewetting.

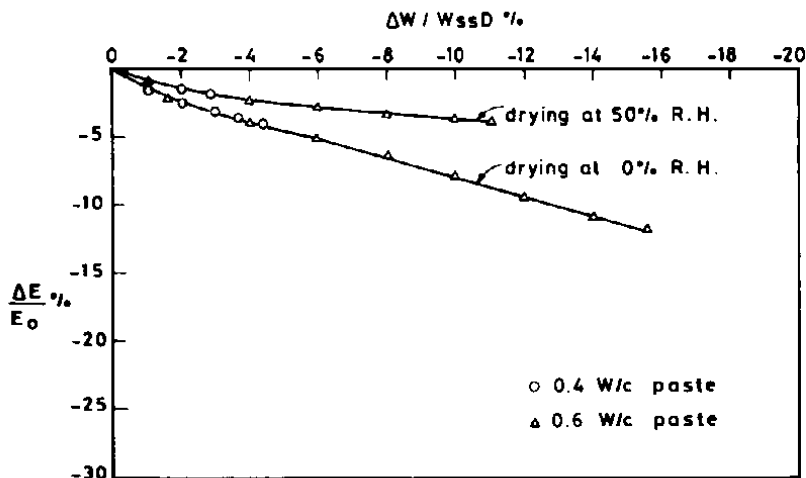


Fig. 7. Dynamic elastic modulus versus weight loss curves for 0.4 and 0.6 w/c pastes

Figure 7 shows that the drop in dynamic elastic modulus increase with increasing severity of drying (lower RH of drying). This trend can be explained by the fact that the rate of shearing increases with increasing the severity of drying. Hence we would expect higher moisture stress gradients with lower RH of drying. And since the drop in elastic modulus is mainly due to the moisture stress gradient, this explains the higher drop in dynamic elastic modulus with higher severity of drying.

The dynamic elastic modulus undergoes a considerable decrease upon drying at 0% RH. This is shown in Figs. 8 and 9 where the changes in dynamic elastic modulus versus the weight changes are plotted. It is clear from these two figures that two drying stages can be identified. Analogous to the drying of concrete by heating [13] the first stage, occurs at the beginning of drying and is characterized by a significant amount of water loss, corresponds to the "constant rate" drying period characterized by convective water movement. The second stage corresponds to the "falling rate" drying period characterized by pendular moisture movement. This stage is considered the most important one with respect to the amount of drop in dynamic elastic modulus. It is characterized by a tremendous decrease in the dynamic elastic modulus associated with little water loss. This stage might also be attributed to the effect of dehydration of interlayer water as suggested by Feldman and Sereda [14, 15, 16] and Parrott [17]. The break point between these states is the "critical point" [13].

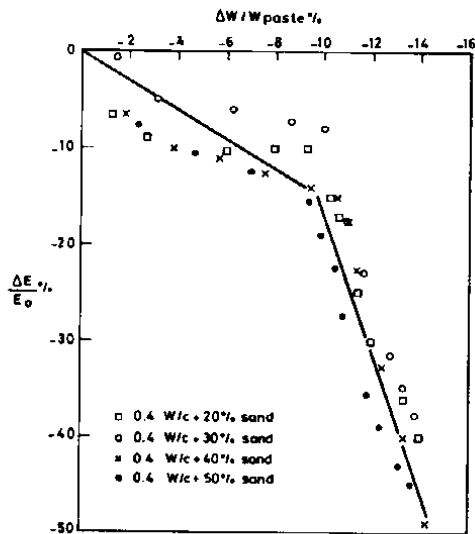


Fig. 8. Dynamic elastic modulus versus weight changes curves for 0.4 w/c mortar dried at 0% RH

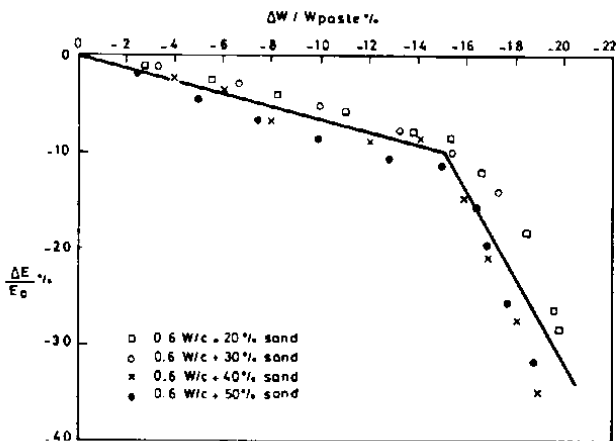


Fig. 9 . Dynamic elastic modulus versus water changes curves for the 0.6 w/c mortar dried at 0% RH

The samples which had been dried at 0% RH were rewetted in steps to minimize any undesirable effects associated with sudden exposure to moisture. This was accomplished by first exposing the samples to 50% RH then to 100% RH and finally the samples were wrapped with wet paper towels. It is apparent that there is no considerable increase in dynamic elastic modulus upon rewetting at 50%. This agrees with findings by Sereda *et al.* [16] who noticed that the dynamic elastic modulus increases after rewetting at RH higher than 50%. Feldam and Sereda considered that interlayer hydration commenced above 30% RH and increased at humidities above 50% RH. Therefore, the rapid increase in the dynamic elastic modulus upon rewetting above 50% RH can be attributed to the re-entry of interlayer water. This was confirmed also from results by Radjy and Richards [7].

The present findings show that drying does not cause microcracking even at very low relative humidities. This is seen from Figs. 1-6 where the original undried dynamic elastic moduli of all the samples studied have been totally recovered upon rewetting. This is in agreement with other investigators [11, 12, 18]. The recovery of original undried dynamic elastic moduli could have been accomplished by autogenous healing of microcracks, created during drying, upon subsequent rewetting. However, this is unlikely to occur and further study is undertaken to verify the absence of microcracking microscopically.

### 5.2. Influence of Aggregate Content on the Drop of Dynamic Elastic Modulus

The effects of aggregate content on dynamic elastic modulus of 0.4 and 0.6 W/C ratios paste and mortar specimens are shown in Fig. 10. The data reported represent

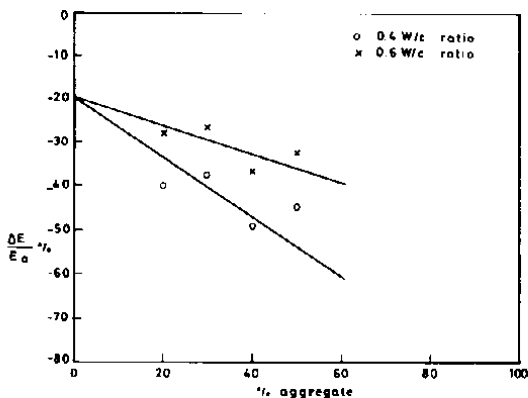


Fig. 10 . Effect of aggregate percentage on the dynamic elastic modulus upon drying at 0% RH

the drop in the elastic modulus caused by drying at 0% RH for 80 days. The results illustrate that the drop in the dynamic elastic modulus increases with increasing aggregate content of the two systems. The results suggest that there may be a linear relationship between the drop in dynamic elastic modulus and the aggregate content. The reason of this is the fact that the aggregate is not subject to hydrometrically induced volume changes, at least not to the extent that paste is. Therefore, during drying, the aggregates present restraint to contraction and therefore become stress concentrations. Obviously the total effect is the sum of the individuals and thus increases with increasing aggregate content.

Figure 10 also shows that the effect of aggregate content is more pronounced in 0.4 W/C ratio than it is in 0.6 W/C ratio systems. The rational explanation for this trend is due to the fact that increasing the W/C ratio increases the permeability and the capillary pores of the paste [19]. This means that the 0.6 W/C ratio mixes contain more and wider channels for the water to drain out during drying with smaller stress gradients than is the case for the 0.4 W/C ratio mixes. Hence the corresponding drop in dynamic elastic modulus is less for higher W/C ratio mixes.

## 6. Conclusions

1. Dynamic elastic modulus-weight loss curves suggest that the changes in dynamic modulus caused by drying and rewetting are mainly due to moisture stress gradients caused by water movement through the specimen, and dehydration of interlayer water.
2. The original undried dynamic modulus is totally recovered through a subsequent rewetting of the dried samples.

3. The drop in the dynamic modulus increases with increasing severity of drying due to the increase in moisture stress gradients.
4. A tremendous decrease in the dynamic modulus upon drying at 0% RH was attributed to the dehydration of interlayer water.
5. An insignificant gain in dynamic modulus upon rewetting up to 50% RH is observed. A rapid increase in dynamic modulus takes place upon rewetting above 50% RH which is attributed to the re-entry of interlayer water.
6. Miniature specimens might be used to measure the real mechanisms of concrete since the effects such as microcracking caused by internal moisture stress gradient can be avoided.
7. The drop in the dynamic modulus increases with increasing aggregate content and decreases with increasing W/C ratio.

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## تأثير عملية التجفيف والترطيب على معامل مرونة العجينة الاسمنتية والمونة

جمال عبدالرزاق المدييم

أستاذ مساعد، قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود،

ص.ب. ٨٠٠، الرياض ١١٤٢١، المملكة العربية السعودية

ملخص البحث: تم في هذه الدراسة فحص تأثير عملية التجفيف والترطيب على معامل المرونة الحركي لعينات تحوي نسبة ٤ر٠ و ٦ر٠ ماء إلى اسمنت من عجينة الاسمنت والمونة. لقد لوحظ أن التجفيف يؤدي إلى نقصان معامل المرونة الحركي بنسبة عالية نتيجة لحدوث اجهاد تدريجي ناجم عن حركة الماء داخل العينة. ولكن القيمة الأصلية للمعامل لكل عينة قبل التجفيف قد استعيدت بالكامل عندما تم ترطيب العينات تدريجياً. لذلك فقد استنتج أن التأثير السلبي مثل الشقق الدقيق والذي ادعى إنه يصاحب عملية التجفيف يمكن منع حدوثه. من هذا يتبين أن العينات الاسمنتية الصغيرة قد تستعمل لقياس الاستجابة غير المحصورة للعجينة الاسمنتية والخرسانية. كذلك أوضحت الدراسة بأن قيمة النقص في معامل المرونة الحركي تزداد مع زيادة كمية الحصى في العينة وتقل مع زيادة نسبة الماء إلى الاسمنت.