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EFFECT OF AGGREGATES ON EARLY AGE FLEXURAL STRENGTH AND MATURITY PREDICTIONS

تأثير وجود الركام على الإجهادات المبكرة للانحناء و تنبؤات نضجها

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خلاصة

يناقش هذا البحث مراقبة مقاومة الانحناء المبكرة فى الخرسانة. و تحص الدراسة دور الركام فى مرحلة النضج المبكرة. تعد طريقة النضج هى أكثر الطرق انتشارا فى صناعة التشييد و خصوصا فى أثناء عمليات تشييد معينة (مثل تشييد المنشات التى تتعلق بأعمال المرور وكذلك الأعمال التى تتطلب فك الشدات سريعا). تستخدم طريقة النضج أيضا فى اعداد برامج كمبيوتر تحاكى تطور الخواص الفيزيقية خلال عملية الهدرجة. و تعتمد طريقة النضج على أساس أن زيادة المقاومة (الخواص الميكانيكية) تتناسب طرديا مع استمرار التفاعلات الكيميائية (الهدرجة) . وتعتبر تمادى التفاعلات الكيمائية دالة فريدة مع كل من الوقت و درجة الحرارة.

تهدف هذه الدراسة أيضا الى أن الركام يمكن أن يؤثر فى هذه العلاقة خصوصا علىمقاومة الانحناء (الشد) المبكرة. ولتحديد هذه الفرضية، فقد تم دراسة علاقة المياه الغير متبخرة مع مقاومة الانحناء على عينات من العجينة الأسمنتية و المونة الأسمنتية وكذلك الخرسانة. و قد تلاحظ من الدراسة وجود علاقة خطية بين مقاومة الانحناء و درجة الهدرجة لعينات المونة الأسمنتية، بينما تلاحظ علاقة خط منكسر فى حالة عينات المونة الأسمنتية و الخرسانة.

تتوقف نقطة الانكسار فى علاقة الخط المنكسر (حالة المونة الأسمنتية و الخرسانة) على اللحظة التى عندها يبدا معظم الركام فى التهشم. يحدث انهيار الانحناء نتيجة انهيار التماسك بين المونة الأسمنتية و الركام فى الأعمار المكرة جدا (أقل من ٦٠ ساعة)، بينما فى الأعمار المبكرة التى تليها يحدث انهيار الانحناء نتيجة التهشم فى الركام نفسه.

ABSTRACT

This article discusses early age flexural strength development in concrete, specifically investigating the role of aggregates and their impact in maturity predictions. The maturity method is becoming more widely used by the construction industry to signal when certain construction operations (e.g., opening to traffic or removing formwork) can be performed. In addition, the maturity method is used in various computer programs to simulate how physical properties develop during hydration. The maturity method is based on the concept that strength (or mechanical property) development is proportional to the extent of chemical reaction (i.e., hydration) that has taken place. It is commonly assumed that the extent of chemical reaction (i.e., the degree of hydration) is a unique function of the product of time and temperature. It is the hypothesis of this work that aggregates can alter this relationship specifically influencing the early age relationship between maturity and flexural (or tensile) strength. To verify this hypothesis the nonevaporable water (i.e., the degree of hydration) was related to the flexural strength development in paste, mortar, and concrete specimens. A linear relationship was observed between the flexural strength and the nonevaporable water for paste specimens, while a bilinear response was observed for both mortar and concrete. The knee point of this bilinear behavior corresponds to the time at which the majority of the aggregates begin to fracture. At very early ages (i.e., less than 2.5 days in this study) the flexural failure behavior is dominated by the paste or bond failure, while at later ages flexural failure is dominated by aggregate failure.

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INTRODUCTION

The rate at which the mechanical properties of concrete develop is strongly influenced by the temperature of the concrete and its surrounding environment. The maturity method has been proposed as an approach to estimate mechanical property development in concrete with variable temperature histories.[1] The basic concept behind the maturity method is that the product of the time and temperature can be used as a unique index to describe the rate of chemical reaction (i.e., degree of hydration) that has taken place. This maturity index can be related to mechanical property development (i.e., strength or stiffness) and used to describe strength and stiffness under the specific temperature history to which the structure is exposed.

The foundation of the maturity method is rooted in the assumption that property development is proportional to the extent of the hydration reaction[2]. An excellent review of the historical development and application of various maturity approaches has been provided by Carino.[3] In one approach the strength of the concrete can be described using a hyperbolic master Curve

$$S = S_{\infty}\left[\frac{k_1(t-t_0)}{1+k_1(t-t_0)}\right] \tag{1}$$

where S_{∞} is the long-term strength, k_t is the rate constant, and t_0 is the offset time, which corresponds to the beginning of strength development.[1] The rate constant accounts for the effects of temperature on property development and is frequently described using the Arrhenius equation.[1,4] Inherently this approach is based on the assumption that temperature changes alter only the rate of the hydration reaction. Despite widespread use, the maturity method must be used judiciously. The precise prediction of strength development using the maturity method requires that the mixture design and constituent materials used to develop the relationship between the maturity and strength are similar to the concrete for which the properties are to be predicted. Graveen et al.[5] recently illustrated that even the slight variations in mixture proportions that can occur during construction should be considered for accurate maturity predictions. It was hypothesized[5] that aggregates play a key role in flexural strength development, and after a specific degree of hydration is achieved the presence of aggregates can alter the maturity–strength gain relationship. Guinea et al.[6] showed that the flexural strength of concrete can significantly vary as a function of quality of paste/aggregate interface. To capture the influence of the properties of each phase, researchers have proposed models to explain aggregate stiffness, strength, and interface energy on the properties of concrete.[7] Wu et al.[8] demonstrated that as the strength of the concrete increases, the aggregates become increasingly important. This chapter builds on these observations and describes an investigation that was conducted to illustrate how the rate constant may be influenced by more than just the hydration reaction of the paste phase depending on the specific property that is being determined. This article describes flexural strength development in paste, mortar, and concrete. The specific intention of this paper is to demonstrate that the use of the maturity method for the prediction of material properties that are dominated by mode I fracture may be complicated by the aggregate phase when it begins to fracture. It is shown that the flexural strength gain is described by the hydration of the paste phase at early ages; however, it is primarily governed by aggregates after a certain degree of hydration is reached. The relationship between flexural strength and degree of hydration exhibits a bilinear behavior when aggregates are present. It is believed that by understanding the composite nature of early age concrete, strength gain and fracture toughness can be better predicted for use in early age damage and failure modeling.

EXPERIMENTAL PROGRAM

This study investigates the flexural strength versus maturity relationship for various cementitious composites. Three series of tests were conducted as described in Table 1. In the first series the water/cement (w/c) ratio was maintained constant while the aggregates we re varied to include a paste (0% aggregate), a mortar (55% fine aggregates by volume), and a concrete (34% of fine aggregates and 36% coarse aggregates). In the second series the w/c was varied for paste and mortar specimens with w/c = 0.30, 0.36, 0.42, and 0.50. In the third series, the type of aggregate was varied to include single size granite and limestone aggregates with w/c = 0.30. A series of tests was performed to better understand how aggregates influence early age mechanical properties. Flexural strength tests were performed to obtain a measure of mechanical property development while ultrasonic pulse velocity measurements were taken to quantify the rate of property development without the influence of aggregate fracture. Losses on ignition (LOI) tests were conducted to provide a measure of the extent of chemical reaction (nonevaporable water or degree of hydration) at each maturity measurement.

The following sections describe the mixture proportions in greater detail. In addition, information is provided about the materials used for this study. Experimental procedures are described along with details of the specimen geometry and specimen preparation. The mixture proportions used in this research are shown in Table I. Ordinary Portland cement was used for all mixtures. In the first series, the aggregate content was varied to make paste, mortar, and concrete specimens. The mortar mixture was designed so that it was similar to the concrete mixture with the coarse aggregates remove d. The paste specimens were similar to mortar and concrete specimens with the aggregates removed. In second series, the w/c ratio was varied to include paste and mortar specimens with w/c = 0.30, 0.36, 0.42, and 0.50. In the third series granite and limestone aggregates we re used with w/c = 0.30. The aggregates that passed through the standard 9.5 mm sieve and were retained on standard 4.75 mm sieve we re used. It should be noted that the aggregates we re selected so that the strengths were considerably different to identify the influence of aggregates on flexural strength–maturity relationship development. These mixtures were designed with only paste and single size aggregates to minimize the influence of sand and aggregate size distribution that could further complicate the interpretation of the results.

Standard practices for making concrete test specimens (ASTM C-192) were followed. The concrete was mixed in a pan mixer, placed in the forms, rodded, vibrated using a plate vibrator, and finished with a steel trowel. The molds were then covered with wet burlap. The specimens tested before an age of 24 h were demolded 10 min before the tests, while the specimens tested after an age of 24 h we redemolded and cured in a temperature - controlled moist curing room (23 ± 1°C, 98% RH) until the time of test.

The temperature of all mixtures was monitored to compute the time temperature history for each mixture.

NONEVAPORABLE WATER

Nonevaporable water content (w_{nevap}) was determined in accordance with ASTM C-114. Paste specimens (w/c = 0.30, 0.36, 0.42, 0.50) were used for the determination of w_{nevap}. At each age, approximately 2 g of paste was ground in a mortar and pestle and immediately placed in an acetone solution to arrest the hydration reaction. The specimens remained in acetone for 24 h before being dried in air for 2 h to allow excess acetone to evaporate.

The specimens were then placed in an oven at 105°C for 24 h. The specimens were then ignited to 1050°C for 12 h and the differences between the weights (105–1050°C) were obtained to calculate w_{nevap} using Eq. 2[9]

$$W_{nevap} = \frac{W_{105^{\circ}} - W_{1050^{\circ}}}{W_{105^{\circ}}} \qquad (2)$$

Where, $W_{105^{\circ}}$ is the weight of sample at 105°C and $W_{1050^{\circ}}$C is the weight of the sample after heating to 1050°C.

FLEXURAL STRENGTH

Two different specimen geometries were used for flexural strength measurement. Smaller specimen geometries were used for the paste and mortar specimens with a length of 300 mm (12 in.) and a cross section of 76 · 76 mm (3 · 3 in.). Larger specimen geometries were prepared for the concrete mixture with a length of 530 mm (21 in.) and a cross section of 152x152 mm (6x6 in.). Flexural specimens were tested in third point loading as specified in ASTM C-78 with a span-to-depth ratio of 3. For the smaller specimens a loading rate of 150 psi/min was used while the larger specimens tested in displacement control used a loading rate of 0.0005 mm/min. The load deflection data was used to compute the elastic modulus (E) of the beams. (Deflection was computed using the average center point displacement of the beam as measured using LVDTs attached to a yoke on either side of the beam.) In addition, ultrasonic pulse velocity (UPV) tests were performed using two 100 mm (4 in.) diameter and 200 mm (8 in.) height cylinders. The elasticity modulus obtained from UPV and load deflection tests were cured under similar conditions to those where the concrete beams were stored. Maturity Measurement The time-temperature history of each mixture was recorded using two thermocouples for paste, mortar, and concrete mixture. The time-temperature histories were then used to calculate the maturities for the corresponding mixtures using Eq. 3.[1]

$$M = \int_{t_o}^{t} \left[k(T) dt \right] \qquad (3)$$

Where, M is the maturity, t is the time, t_o is the offset time, and $k(T)$ is the rate constant at temperature T.

EXPERIMENTAL RESULTS

SERIES I: COMPARISON OF PASTE, MORTAR, AND CONCRETE

The flexural strengths of the paste, mortar, and concrete specimens were obtained in the first test series at various ages, and the strength prediction curves (Eq. 1) were prepared using the maturity method as outlined by Carino.1 Figure 1 shows the variation of flexural strength development for paste, mortar, and concrete mixtures as a function of maturity (w/c = 0.42). Though the early age flexural strength looks similar for paste, mortar, and concrete specimens, it should be noted that it was different at later ages. It is the hypothesis of this chapter that these differences may be attributed to the presence of aggregates. It should be noted that the hyperbolic strength curve is able to predict the strength development for all these series (paste, mortar, and concrete). However it was observed that the rate constants for the paste, mortar, and concrete mixtures were not the same. Figure 1. Flexural strength maturity master curve for Series I: Paste, mortar, and concrete with w/c = 0.42.

Figure 2 shows the flexural strength development for concrete, mortar, and paste as a function of nonevaporable water (w_{nevap}, which is proportional to the degree of hydration). The relationship between nonevaporable water was bilinear for strength development of mortar and concrete while the paste specimen still showed a linear response. The slope between the strength and nonevaporable water is similar at low nonevaporable water contents (i.e., low degree of hydration) for paste, mortar, and concrete, although it should be noted that the flexural strength of the mortar specimens was less than that of the paste for the same nonevaporable water content, and the concrete specimen was even lower. It is currently believed that Figure 2. Flexural strength versus nonevaporable water (proportional to degree of hydration) for Series I: Paste, mortar, and concrete with w/c = 0.42 this may be due to either the presence of very weak aggregates or an interface that is weaker than the strength of the paste. Further research is needed to clarify the exact reason for the lower strength in the mortar and concrete systems.

SERIES II: INFLUENCE OF WATER/CEMENT RATIO

The nonevaporable water content was determined for paste specimens with various water/cement ratios and correlated with flexural strength gain. Figure 3 illustrates the strength versus nonevaporable water in the paste specimens with varying water/cement ratios. It can be observed that the strength development is linearly proportional to the nonevaporable water, indicating that the strength development in the paste is directly related to the extent of the hydration reaction that has taken place. As such it appears that the application of the maturity method to describe the rate of strength development of paste would be relatively straightforward with a change in the time-temperature history would result in a change in the degree of hydration (i.e.,nonevaporable water content).

The flexural strength development of the mortar specimens with a varying w/c value as a function of nonevaporable water is shown in Fig. 4. Unlike the paste behavior (Fig. 3), the flexural strength of the mortar specimens (Fig. 4) again showed a bilinear relationship with nonevaporable water (DOH). The knee point in the bilinear mortar curves (point of change in slope) is related to the behavior of aggregates, representing the critical DOH where a single volume of aggregate begins to fracture. It is worth noting that the initial rate of flexural strength development in the mortar is very similar to the rate of flexural strength development of paste until the knee point is achieved. It is believed that at early ages the crack propagates around the aggregates. Therefore, at low DOH the failure is predominantly dependent on the paste strength governed by the hydration reaction. The presence of aggregates does not appear to substantially affect the rate of strength development at these early ages and only slightly reduces the strength. This reduction in strength is presumably due to either the fracture of a small portion of aggregates or the potential low strength (high porosity) of the interfacial region around the aggregates at early ages. Figures 2 and 4 indicate that after the knee point, the rate of flexural strength development is significantly lower than the initial rate of strength development. (Recall that the initial rate of strength development in the mortar and concrete specimens is approximately equal to the rate of flexural strength development in the paste specimens.) It should be noted that the knee point appears to correspond with the time at which the visual observations of the crack surfaces show fractured aggregates. Further evidence is presented later in this paper for a more quantitative assessment of the fraction of the aggregate that has fractured at each stage of the test.

The time when the aggregates began to fracture, as determined using visual observaticns, for all these mixtures appeared to correspond to the knee point. It should be noted that the aggregates used in all of the mixtures (i.e., at all w/c ratios) we re similar (i.e., the same source, gradation , and volume). The knee point that was observed in lower strength (higher w/c ratio) materials appears to illustrate that a greater degree of hydration is required to cause the aggregate to fracture. As expected, the mixture with a lower w/c ratio (i.e., 0.30) appears to develop strength or interface bonds more rapidly, therefore the lower w/c ratio mixture reaches the knee point at an earlier age than mixtures with a higher w/c ratio. It should be noted that the rate of the flexural strength development for each paste mixture was similar; however, the rate of strength development of mortar specimens reduced from mixture with 0.30 w/c ratio to a mixture with a 0.50 w/c ratio.

The fractured surfaces of the concrete beams were visually examined to determine the proportion of aggregates fractured at each testing age. It is noted that, two fracture surfaces from beams tested at an age of 12 and 72 h. The specimen tested at 12 h shows that the crack propagates around the coarse aggregate, while the specimen tested at 72 h shows that the crack propagating through the coarse aggregate. To better quantify the visual observations the aggregate fracture density (AFD) was calculated for each fractured surface. The AFD was computed

as the ratio of the number of fractured aggregates to the total number of coarse aggregates in the fractured surface. All coarse aggregates (approximately greater than 4.75mm) were counted and classified as either un-fractured or fractured. The aggregate fracture density was observed, supporting the hypothesis that the knee point behavior corresponds with aggregate fracture. A low number of aggregates were fractured at the early age where the failure was dominated by the paste matrix or the bond. At an early age (i.e., 12 h) the AFD was only 16%, which corresponds with the fact that the majority of the aggregates were undamaged as the crack propagated around them. After the knee point was reached a more substantial percentage of the aggregates were observed to have fractured. For example, at an age of 2 days, the AFD was observed to be 64%, which showed that most of the aggregates were fractured. And at 6 and 28 days the AFD was calculated as 82% and 92%, respectively, verifying that almost all of the aggregates were fractured.

SERIES III: VARIATION IN AGGREGATE TYPES

To better understand how the knee point was related to the effects of strength of aggregates, two additional mixtures were prepared in the third series. The mixtures were prepared using a constant w/c ratio and single size granite or limestone aggregate using the mixture proportions provided in Table I. Again flexural beams were prepared (with a length of 300 mm [12 in.] and cross section of 76 · 76 mm [3x3 in.]) and tested in flexure.

Figure 5 shows the flexural strength behavior of these beams as a function of nonevaporable water along with the flexural strength behavior of paste specimens. It can be seen that the knee point occurs at different nonevaporable water contents for the mixtures with the two different aggregates. It should be noted that the initial strength gain was similar for the mixtures with aggregates and the pure paste mixture up to the knee point. After the knee point, however, the aggregates influence the strength at failure. Again the AFD was calculated for these mixtures as shown in Fig. 5. Since limestone is weaker than granite, it was expected that the knee point for the limestone mixture would occur at a lower paste maturity (i.e., lower degree of hydration), which can be observed in Figure 6.

ELASTIC MODULUS BEHAVIOR

The elastic modulus was calculated for the concrete beams using the load displacement data (measured using the average of two LVDTs mounted on either side of a yoke on the beam). The slope of the load displacement response was used to calculate the elastic modulus using the standard displacement equation for simply supported elastic bend under third point loading. In addition, the elastic modulus of the same mixture was calculated using information from the ultrasonic pulse velocity.

Figure 7 shows the variation in elastic modulus (of the beams) as a function of the nonevaporable water (i.e., degree of hydration). The elastic modulus varies as a linear function of the nonevaporable water and no knee point is observed. Even though this initially may not seem logical in view of the previous discussions on the knee point observed for the same beams in describing the flexural strength, it should be noted that the elastic modulus depends on the behavior of the specimen under very low levels of loading. At these low load levels it can be assumed that the concrete has not developed significant damage and there fore that the aggregates have not fractured, and as such do not influence the elastic modulus development. This approach may explain the observations of Rostasy et al., who note that the elastic modulus increases at a much different rate than flexural strength.

However, further work is being conducted to ascertain whether this is the source of these differences.

A PRELIMINARY CORRECTION FOR MATURITY PREDICTIONS THAT CONSIDER AGGREGATES

A very preliminary approach is presented below to incorporate the behavior of aggregates in the prediction of a maturity-strength relationship for concrete.

In this discussion an approach can be used that considers the concrete as a composite material of a paste matrix phase and an aggregate phase. It could be imagined that the flexural strength of a two-phase composite could be approximated using a standard composite law of mixtures approach as shown in Eq.4.

$$\sigma_{r-conc} = \sigma_{paste} V_{paste} + \sigma_{agg} V_{agg} \qquad (4)$$

Where $\sigma_{r\text{-conc}}$ is the flexural strength of concrete, σ_{paste} is the strength of the paste, σ_{agg} is the strength of aggregates, V_{paste} is the volume fraction of the paste, and V_{agg} is the volume fraction of the aggregates. (Note that in this approach it is assumed that the elastic stiffnesses are similar enough that they do not require substantial corrections like those more commonly proposed in fiber-reinforced composites.[10] However, based on the previous discussion this approach would need to be modified to reflect the fact that the aggregate contribution changes as a function of the degree of hydration. It can be assumed that the flexural strength of concrete at early ages has a failure that is dominated by the paste phase (i.e., before the knee point).

The strength development of the paste phase can be predicted using the hyperbolic strength development curve as previously described. At early ages the aggregates are stronger than the paste phase, therefore the fracture takes place around the aggregate entirely through the paste phase. As such the fracture surface shows that the crack is essentially 100% through the paste phase. If we neglect the fact that the fracture path will be longer than the path straight across, a paste specimen, the flexural strength at early ages can therefore be approximately predicted using Eq. 5.

$$\sigma_{r-conc} = \sigma_{r-paste} \tag{5}$$

where $\sigma_{r\text{-paste}}$ is the flexural strength predicted using maturity method of the same w/c ratio paste system.

At later ages (i.e., after the knee point) the failure is attributed to the contribution of both paste matrix and aggregates to the strength of concrete (Eq. 4) and can be estimated using the approach described in Eq. 4, which has been rearranged in Eq. 6.

$$\sigma_{r-conc} = \sigma_{r-paste} - (\sigma_{paste} - \sigma_{agg})V_{agg} \tag{6}$$

Assuming a tensile strength of 3.80 MPa for a limestone aggregate, the results obtained from the experiments and from Eq. 6 are similar and appear to capture the later age behavior (after the knee point).

Though it has been proposed that early age strength is a function of paste behavior alone, it should be noted that at early ages the mixtures with aggregate inclusions show slightly lower values of flexural strength as compared to the corresponding flexural strength values of paste specimens at similar ages. This behavior is currently thought to be attributed to stress concentrations around the aggregates and an increasing volume of the interfacial transition zone material that may be weaker than the paste; however, further research is needed to verify these hypotheses.

CONCLUSIONS

This chapter described the early age flexural strength behavior of paste, mortar, and concrete. A linear relationship was shown to exist between the flexural strength and nonevaporable water (i.e., degree of hydration) for paste specimens. However, as aggregates are added to the paste (i.e., mortar and concrete) , a bilinear relationship is observe d. This bilinear behavior occurs because the paste dominates failure at very early ages; however, at later ages the aggregates dominate the failure response. The rate of development of elastic modulus differs from that of flexural strength. Aggregates do not affect the elastic modulus in the same way they affect the flexural strength development.

Table (1) : Mixture proportions

Test series	Mixture	w/c	Cement content (kg/m^3)	Vol. % of agg.			Experiment performed
				FA	CA	Total	
I. Comparison of paste, mortar, and concrete	Paste	0.42	1355	-	-	-	Flexural strength and ultrasonic pulse velocity
	Mortar	0.42	561	55	-	55	
	concrete	0.42	320	34	36	70	
II. Influence of water/cement ratio	paste	0.3	1620	-	-	-	Flexural strength and loss in ignition
		0.36	1475	-	-	-	
		0.42	1355	-	-	-	
		0.5	1223	-	-	-	
	Mortar	0.3	728	55	-	55	
		0.36	664	55	-	55	
		0.42	561	55	-	55	
		0.5	550	55	-	55	
III. Influence of aggregate type	Paste	0.3	1620	-	-	-	Flexural strength
	Granite mortar	0.3	1133	-	30	30	
	Limestone Mortar	0.3	1133	-	30	30	

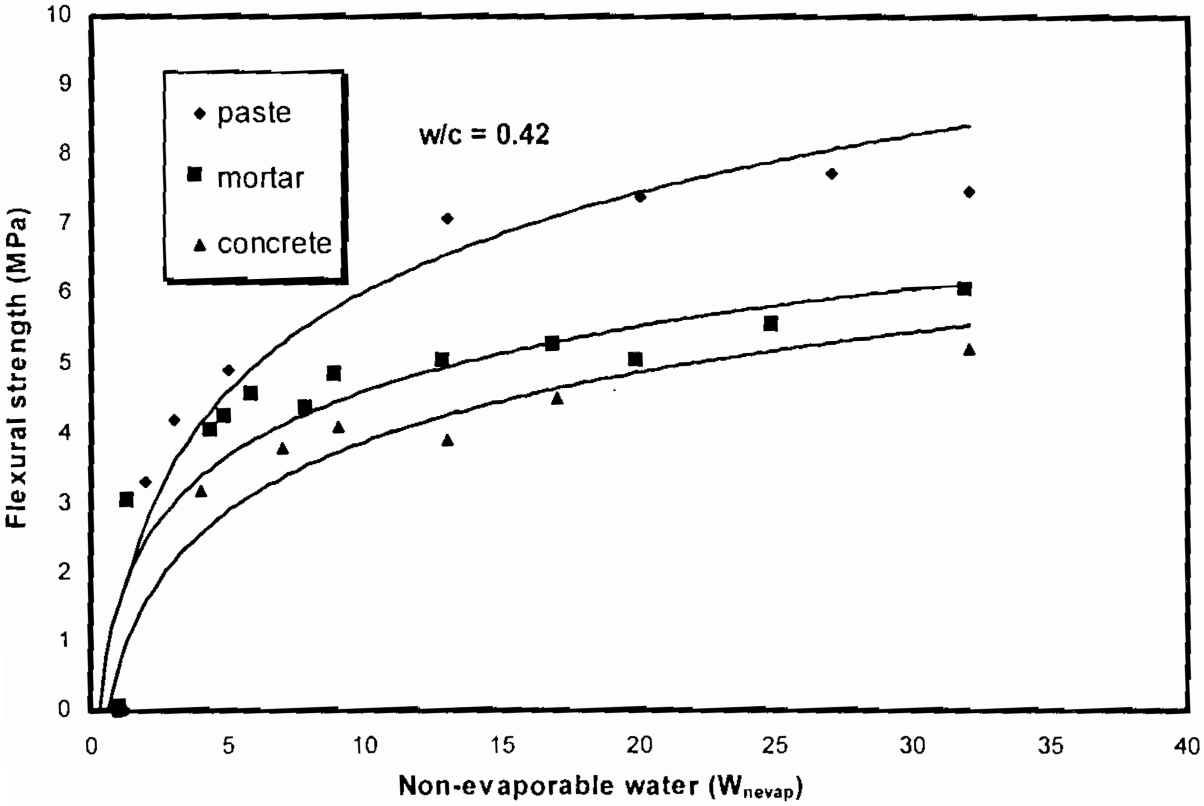

Fig. (1) : Flexural strength maturity master curve for series I: Paste, mortar, and concrete with w/c = 0.42.

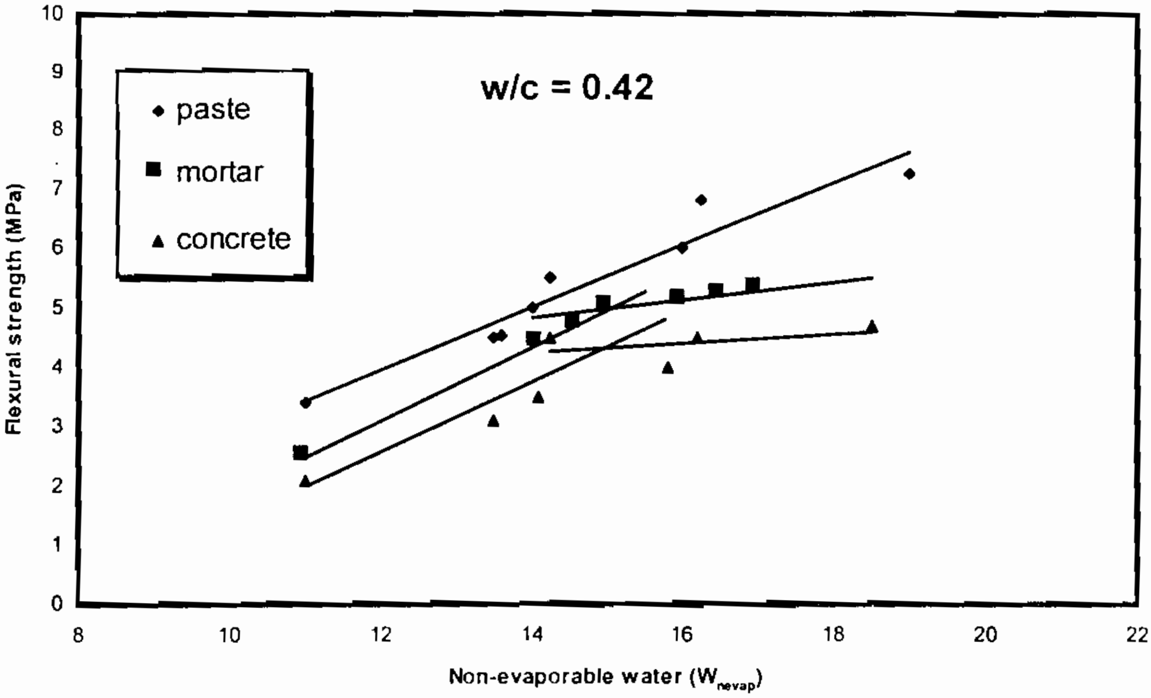

Fig. (2) : Flexural strength versus non-evaporable water (for series I: Paste, mortar, and concrete with w/c = 0.42).

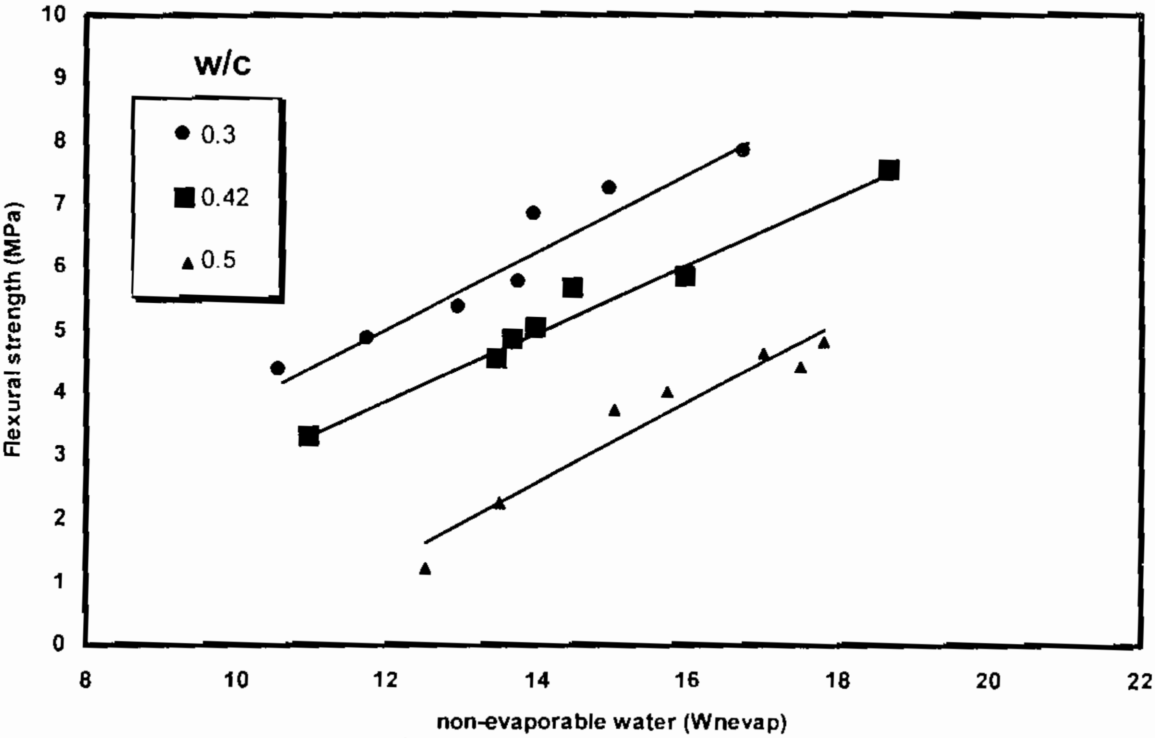

Fig. (3) : Flexural strength versus non-evaporable water (for series II: paste with w/c = 0.3, 0.42, and 0.5).

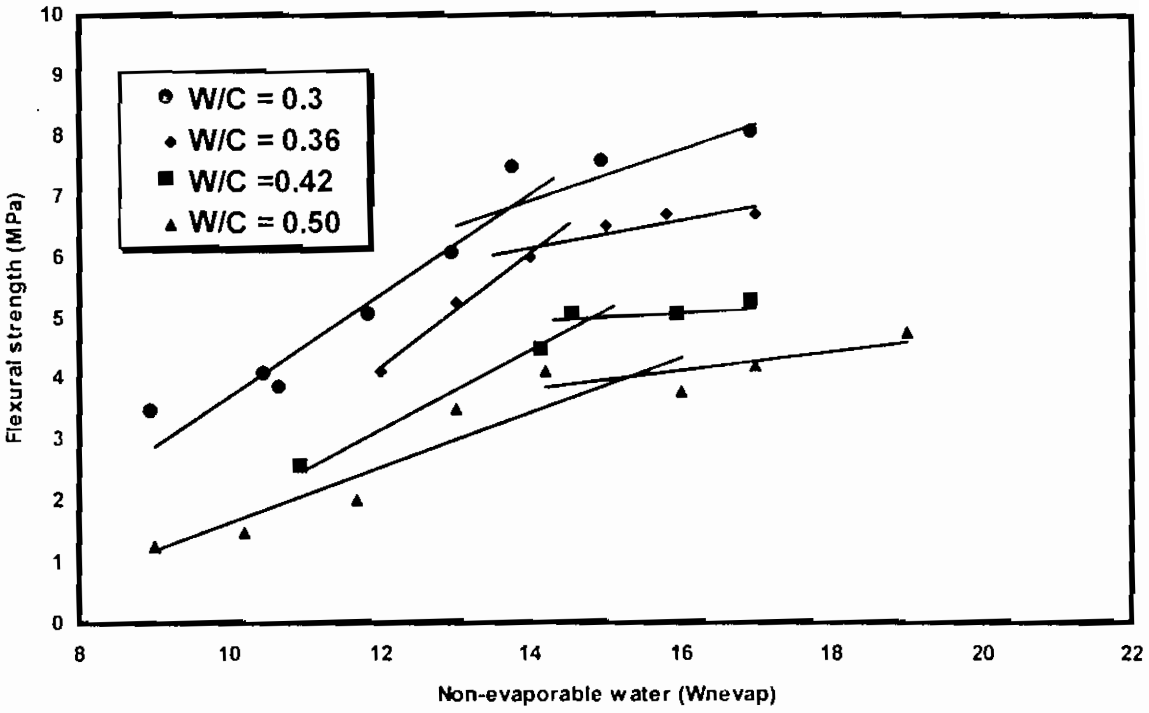

Fig. (4) : Flexural strength versus non-evaporable water (for series II: mortar with w/c = 0.3, 0.42, and 0.5).

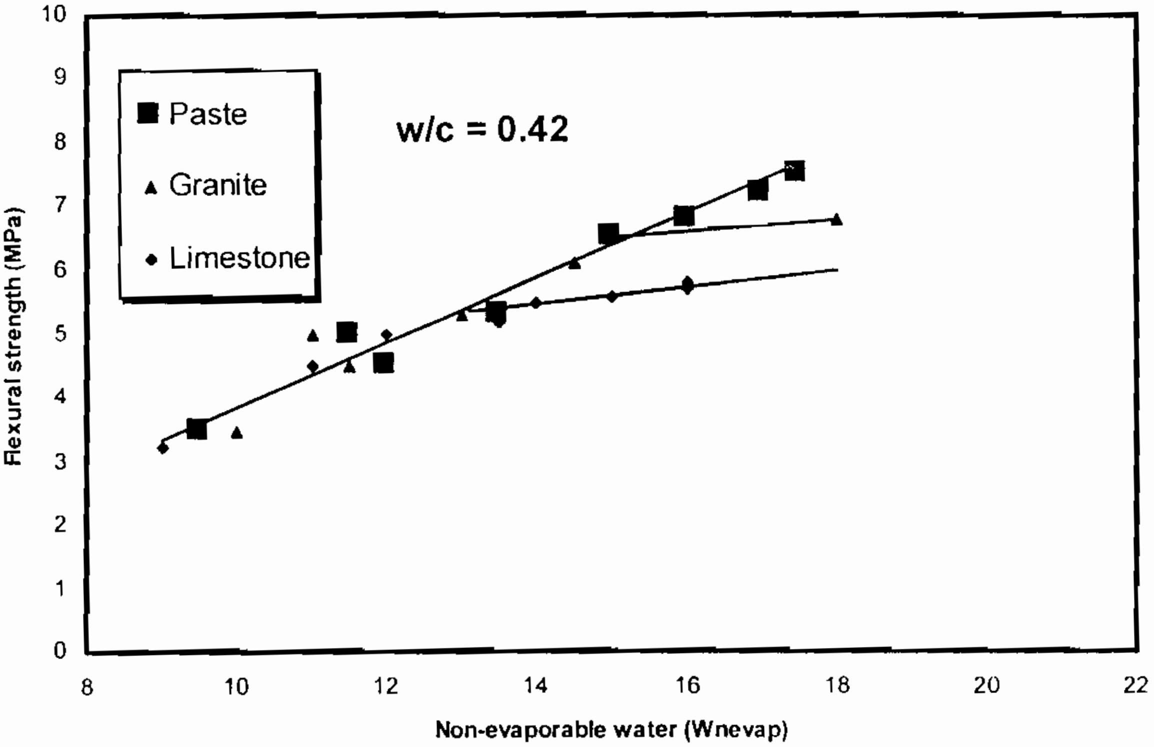

Fig. (5) : Flexural strength versus non-evaporable water content (for paste, limestone, and granite).

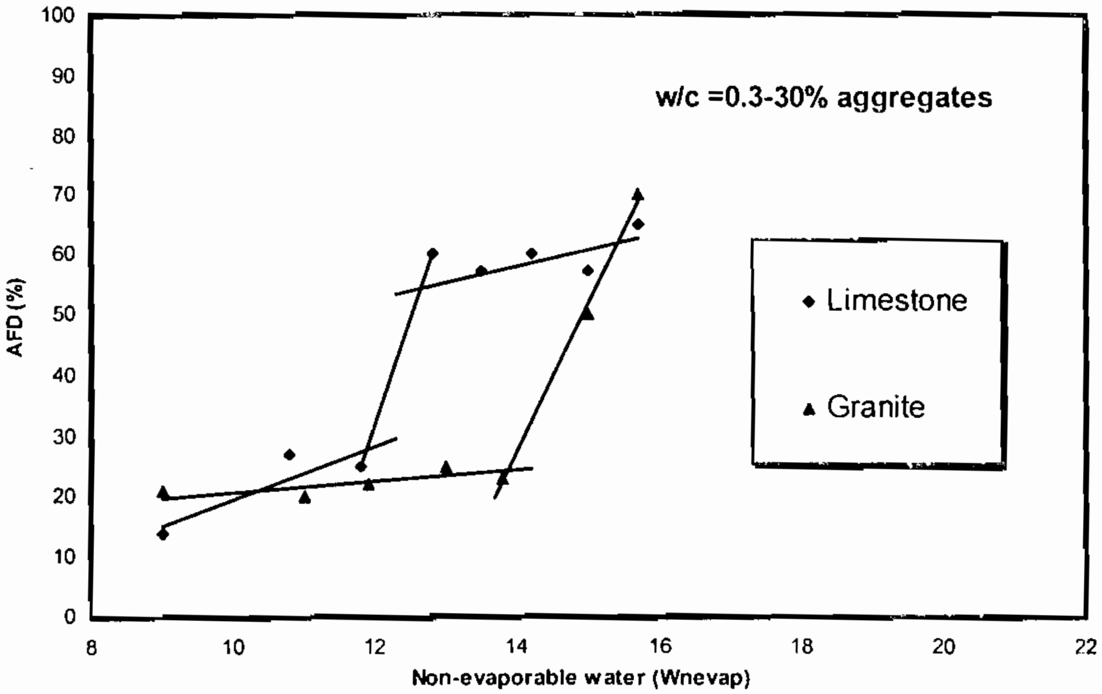

Fig. (6) : Aggregate fracture density of concrete containing either granite or limestone aggregates.

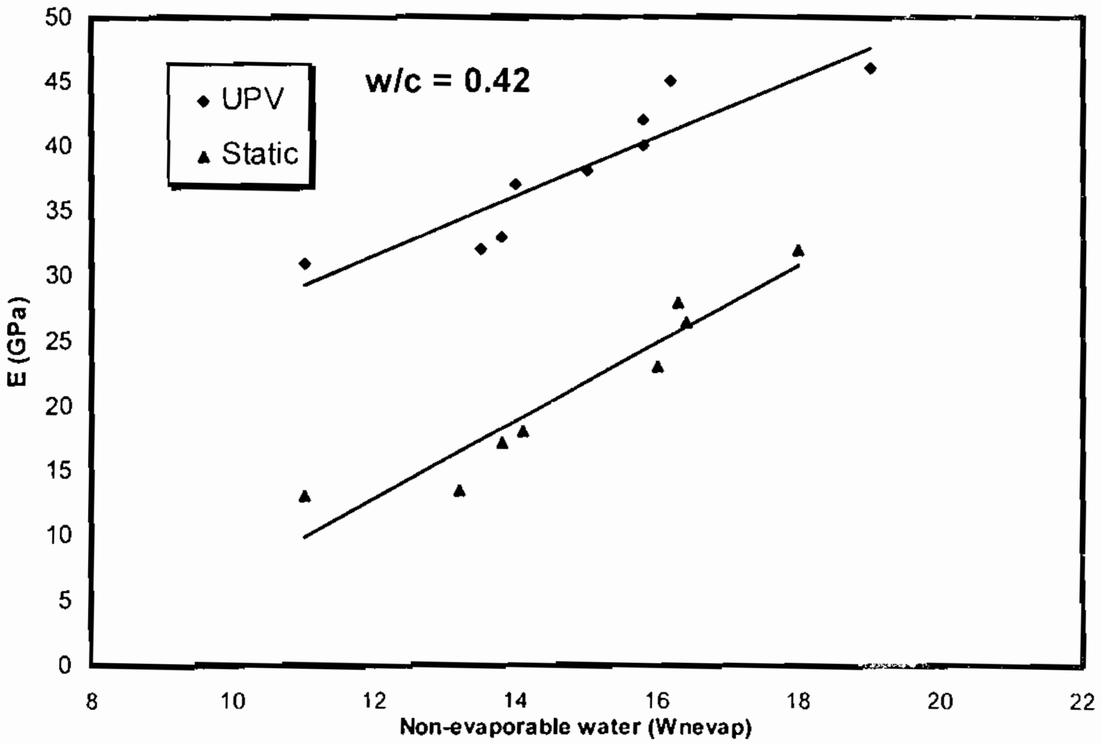

Fig. (7) : Elastic modulus versus non-evaporable water (for series I : concrete with w/c = 0.42).

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