

Assessment of Wood-Cement Compatibility: A New Approach

By Sukhdeo Rao Karade, Mark Irle and Kevin Maher

Buckinghamshire Chilterns University College, High Wycombe (UK)

A version of this paper has been published in *Holzforschung*, 2003, 57:672:680.

Assessment of Wood-Cement Compatibility: A New Approach

By Sukhdeo Rao Karade, Mark Irle and Kevin Maher

Buckinghamshire Chilterns University College, High Wycombe (UK)

Summary

The influence of wood upon the setting of cement is generally assessed by conducting semi-adiabatic hydration tests. The existing methods to quantify wood-cement compatibility are based on the maximum hydration temperature (T_{max}), the time (t_{max}) to reach it or the heat evolved in a specified period. Results obtained by these methods at higher wood-cement ratios are not convincing and show inconsistencies for various reasons. This paper discusses these reasons and suggests an alternative method based on a maturity function. The results from the new calculation method are compared with those of the existing methods and demonstrate the superiority of this new method at higher wood-cement ratios.

Keywords

Cement

Wood

Compatibility

Cork

Composite

Calorimetry

Hydration

Retardation

Extractives

Introduction

Wood, in various forms, has been mixed with cement to make composite materials for about 100 years. Much of the research in this area has been done in the last 40 years because of the growing concern about the health hazards associated with the use of asbestos fibre (Coutts 1988; Moslemi 1999). Initial research revealed that not all wood species are compatible with cement because some retard the setting of cement (Sandermann *et al.* 1960; Weatherwax and Tarkow 1964). The compatibility of wood with cement has also been found to vary within a species dependent on where the tree was grown (Hachmi *et al.* 1990) and which part of the tree is added (Miller and Moslemi 1991b). Therefore, various attempts have been made to accurately assess the compatibility of wood and other organic aggregates with cement. The methods that various researchers have used include: the measurement of hydration characteristics of a cement-aggregate mix (Sandermann and Kohler 1964; Weatherwax and Tarkow 1964; Hachmi *et al.* 1990); the comparison of the mechanical properties of cement-aggregate mixes (Hong and Lee 1986; Lee *et al.* 1987; Demirbas and Aslan 1998); and the visual assessment of microstructural properties of the cement-aggregate mixes (Ahn and Moslemi, 1980; Davies *et al.* 1981).

Researchers most commonly use the measurement of hydration temperature because of the simplicity of the test. However, interpretation of the results is difficult due to the complexity of the cement hydration process. The situation is further complicated by the incorporation of wood or other organic particles in the cement paste. Currently, there is no standard method of measuring the hydration temperature of cement-organic aggregate mixes. Attempts have been made to correlate hydration characteristics with strength properties but the results are inconclusive (Dass 1974; Hong and Lee 1986; Lee *et al.* 1987; Miller and Moslemi 1991a). For example, addition of wood, even if it slightly retards the setting of cement, can improve the tensile and bending properties due to a reinforcing effect. Wood cannot, however, improve compressive strength because the compressive strength of cement is much higher than that of wood.

This paper reviews the available methods and their limitations and finally suggests a new method for assessing wood-cement compatibility, which can also be used to assess the influence of cement admixtures like accelerators, retarders and plasticisers.

A Review of the Conventional Methods

When water is mixed with cement, setting of the cement starts, which refers to the solidification of the cement paste. *Initial setting time* indicates the start of solidification. After some time the cement paste becomes fully rigid. The time when this occurs is called *final setting time*. Vicat's apparatus is widely used to determine the setting time of cement (Mehta and Monteiro 1993); this measures the resistance of cement paste to the penetration of a needle. An alternative test, called Gillmore needle, described in ASTM C 266-89 is also used. However, it gives higher values of setting times (Neville 1995). The Vicat or Gillmore needle tests can be used to assess the effects of various set-control admixtures for cement. For example, Bruere (1963) studied the effects of retarders and Roskopf *et al.* (1975) studied the effect of accelerators using these tests. Unfortunately, these techniques cannot be used for wood-cement composites because the presence of wood particles may interfere with the penetration of the needle. A procedure is given in ASTM C 403-92 for determining the setting time of concrete by sieving the mortar from the fresh concrete and then using a Proctor penetration probe. However, Neville (1995) points out that this test measures a different property than the setting time of cement, probably because the results obtained by the Proctor penetration probe test are in terms of strength. Consequently, tests based on heat of hydration of cement are generally applied to organic aggregate-cement mixes.

To measure the hydration temperature, cement and water are first mixed in a predetermined ratio and the mix is then kept in a thermally insulated container. Nonetheless, complete heat insulation is impossible and some heat may still escape to the surrounding air. The test is thus carried out in semi-adiabatic conditions, for which a maximum heat loss rate limit of $100 \text{ J h}^{-1}\text{K}^{-1}$ is proposed by RILEM (1997) and a European standard (prEN: 196-9, 1997). The temperature of the mix is recorded at suitable intervals over a period, generally 24 hours. A comparison is made between the hydration characteristics of a wood-cement mix and a neat cement sample in order to assess the wood-cement compatibility. The various cement hydration-based methods presented in the literature are summarised in Table 1.

The maximum hydration temperature (T_{max}) is a comparatively easy and simple tool for rating the wood-cement compatibility. Unfortunately, T_{max} is highly susceptible to experimental parameters like the type of cement and calorimeter, wood:cement:water ratio, wood particle size, level of mixing and water absorption of wood. It is, therefore, difficult to obtain the same results in varying laboratory conditions. Recently, Brandstetr *et al.* (2001) found that the insulating

conditions greatly influenced T_{max} of the cement-water mix.

The compatibility assessment methods given in Table 1 use a similar wood:cement:water ratio of either 20:200:100 or 15:200:90.5, compositions which were initially suggested by Sandermann and Kohler (1964) and Weatherwax and Tarkow (1964), respectively. The wood particle size generally used for these tests is very fine. For example, Weatherwax and Tarkow (1964) used 0.1 to 0.25 mm size, whilst Hachmi *et al.* (1990) used 0.425 to 0.85 mm size particles. It must be noted that these parameters have very limited practical relevance because, in practice, much higher wood:cement ratios and larger particles are used. It has also been found that the inhibition of cement setting increases with increasing fineness of wood particles (Weatherwax and Tarkow 1964). Semple *et al.* (1999) also showed that compatibility test results using wood flour did not match those with wood wool. It appears that the compatibility tests that use relatively fine particles are suitable for comparing the compatibility of different wood species in the laboratory, but in the real manufacturing conditions where different particle sizes are used this comparison may not be valid. That is to say, a wood found to be incompatible using fine particles might be compatible with coarse particles. The use of fine particles, however, can provide valuable information on the maximum possible effect of wood-extractives, as finer particles expose more surface area to the cement paste and thus more extractives can enter into the solution.

Weatherwax and Tarkow (1964) calculated the required amount of water for their hydration tests to be 0.25 ml per gram of cement and 2.7 ml per gram of wood, which appears to be a rule of thumb, and several researchers have followed it subsequently. For example see: Biblis and Lo (1968); Zhengtian and Moslemi (1985); Lee *et al.* (1987) and Hachmi *et al.* (1990). The fixed water:cement ratio is generally used for all wood species. However, different species absorb different amounts of water such that a variable amount of free water may be available for cement, and thus influence T_{max} . For manufacturing wood-cement particleboards, Simatupang (1979) reported that the optimum water requirement was approximately inversely proportional to the wood particle density.

Most of the compatibility assessment methods given in Table 1 compare parameters based on T_{max} or t_{max} of a wood-cement mix with that of neat cement. The problem with the methods based on T_{max} is the greater heat capacity of the wood-cement mix, because of the additional mass of wood and water. The greater heat capacity will lower T_{max} of the mixture compared to a neat cement-water mix. So even if there is no retardation, the hydration of a

wood-cement mix progresses at a lower temperature and in turn results in a lower reaction rate, which further reduces T_{max} and the heat evolution rate of a wood-cement mix. This is because temperature greatly affects the hydration rate of cement (Kjellsen and Detwiler 1992) having a particularly pronounced effect in the early stages of hydration (Odler, 1998). The magnitude of the effect of temperature on cement hydration can be realised in Figure 1. The graph shows relative rate of heat of hydration at various temperatures with respect to heat evolution rate at 20 °C. The heat evolution rates were calculated using the well-known Arrhenius equation (Lawrence 1998):

$$Q = Ae^{\frac{-E_a}{RT}} \quad [8]$$

Where Q is heat of hydration rate at an absolute temperature, T , expressed in Kelvin (K); A is a proportionality constant, which cancels out when relative hydration rate is determined; E_a is the apparent activation energy of cement (J/mol) and R is the gas constant (8.314 J/mol-K). A value of 4000 is recommended for E_a/R by RILEM for the hydration of Portland cement above 20 °C (RILEM 1997).

Brandstetr *et al.* (2001) found that a greater quantity of cement at the same water:cement ratio resulted in higher T_{max} values. It indicates that T_{max} values depend upon the mass of cement. It has been found that 200 g of neat cement rises the temperature above 80 °C (Sandermann *et al.* 1960; Hofstrand *et al.* 1984; Hachmi *et al.* 1990). Such high temperatures certainly influence the hydration rate (Figure 1) and cannot be directly compared with that of wood-cement mixes, which tend to achieve a maximum hydration temperature of about 50-60 °C. Thus, use of a smaller quantity of cement can reduce the temperature differences between neat cement and wood-cement mixes.

A counter-effect to those described above is that the greater volume of a wood-cement mix may lower the rate of heat loss, which might affect T_{max} and t_{max} . Thus, a direct comparison of T_{max} and t_{max} or the inhibitory indices based on these parameters could be erroneous. These problems could be avoided by using isothermal conditions. Unfortunately, due to the high volume of the mix and experimental complications, it is difficult to conduct these tests in isothermal conditions.

Hachmi *et al.* (1990) recommended the C_A factor over the C_T and C_H factors. The C_A factor is based upon the total heat generated within a specified period. This approach is better than the others because it takes into consideration the heat capacity of Dewar flask and mix of constituents. Consequently, many researchers adopted this approach for comparing the

compatibility of various wood species and for their classification. For example, refer to Semple *et al.* (1999) and Hemawan *et al.* (2001). A limitation of the C_A factor is that it represents total heat generated but does not indicate the intensity of reactions. Neville (1995) suggests that intensity of the hydration process is practically more important because the total heat may spread over a time. Furthermore, it has been observed that even if there is no second hydration temperature peak, the C_A factor still indicates a level of compatibility. For example, the hydration data for *Quercus ilex* L. reported by Hachmi *et al.* (1990) showed that there was no rise in hydration temperature after the first peak. This shows that the nucleation of calcium silicate hydrates (CSH) had not started. In hydrated cement, CSH provides the bonding between components (Mehta and Monteiro 1993) and so, no bonds are likely to form in a *Quercus ilex* L. wood-cement mix. However, possibly due to the initial hydration peak, the C_A factor reported was still 37% and, according to the classification index suggested by Hachmi and Moslemi (1989), *Q. ilex* is moderately suitable for making wood-cement composites. Clearly, this does not make sense.

From this discussion, it is clear that determining the effect of wood on the hydration of cement is not a trivial matter. The tests based on T_{max} and t_{max} using low wood:cement ratios under similar laboratory conditions can reveal some useful preliminary information within a short period about the comparative wood-cement compatibilities for various wood species. However, the same tests cannot be used to study the effect of varying quantity of wood and particle size. While the quantity of heat generating component cement remains constant, the increasing mass of wood in the mix generally decreases T_{max} and increases t_{max} . With these parameters, one cannot ascertain whether these effects are due to increasing mass (and thus heat capacity) or increasing extractives. A similar argument applies for particle size. A finer particle size requires more water. Thus, the total mass of the mix increases and, due to higher fineness, surface area and the amount of extractives increases. Consequently, the same wood has different compatibilities depending upon its form and proportion in the mix. This suggests that the existing methods are susceptible to varying test parameters. Therefore, there is a need to develop a compatibility method that can take into consideration the varying parameters, such as amount of wood, water:cement ratio, temperature of hydrating sample and cooling rates; and that can reflect the compatibility at different wood:cement:water ratios. Moreover, the compatibility index should reflect the intensity of the hydration process. For optimisation, it is also desirable to test the wood with different particle sizes.

Proposed Alternative Method

This method combines the effect of time and temperature on the hydration of cement-aggregate mixes and is similar to the maturity method used by concrete technologists to assess the strength of concrete cured at higher temperatures. Carino and Lew (2001) reviewed various maturity methods. Freiesleben Hansen and Pedersen (1977) proposed a maturity function to compute the equivalent age of concrete, which was based on the Arrhenius equation. This maturity function can be applied to determine the 'equivalent age' (t_e) of various hydration samples that undergo different temperature histories. The following relationship gives the 'equivalent age' at any instance i .

$$t_e = \sum_0^i e^{\frac{-E_a}{R} \left(\frac{1}{T} - \frac{1}{T'} \right)} dt \quad [9]$$

Where ' E_a ' is the apparent activation energy of cement (J/mol), R is the gas constant (8.314 J/mol-K), T and T' are absolute specimen and reference temperatures (Kelvin), respectively.

By differentiating the total heat evolved with respect to the 'equivalent age' or 'equivalent time', the heat evolution rate (Q_e) can be obtained. Now, the compatibility of the wood-cement mix can be assessed by comparing the maximum heat evolution rate ($Q_{e\max}$) and the 'equivalent time' ($t_{e\max}$) required to reach $Q_{e\max}$. Double (1983) successfully classified various accelerators and retarders, and rated them by plotting the maximum heat rate against the reciprocal of time to reach the maximum heat rate. The compatibility is, thus, proportional to the maximum heat rate and inversely proportional to the time to reach it. If these two effects on hydration are combined by multiplying them and by taking a geometrical mean because the two effects are compared, the compatibility index (CI) can be expressed in percentage by equation [10], as follows:

$$CI = \sqrt{\left(\frac{Q_{e\max} t'_{e\max}}{Q'_{e\max} t_{e\max}} \right)} 100 \quad [10]$$

Where the parameters qualified with an apostrophe represent neat cement and others refer to a wood-cement mix.

Materials and Methods

These experiments form a part of a research project on cork-cement composites. One of the objectives of the project is to understand the effect of cork content and granule size on hydration

of cement. The materials used in the present experiment are ordinary Portland cement (42.5 N grade), and additives like cork granules (mean particle size 0.83 mm), cork dust (mean particle size 0.1 mm), and ordinary sand. For each test, 100 g of cement was used. For cork-cement mixes, the amount of cork varied between 10 to 30% by weight of cement in steps of 10%. With sand only one composition with sand:cement ratio 100:100 was used. Three replicate tests were conducted for each composition. For each replication, a different flask was used. Since the property of cement is compared in all the indices, six replicate tests were conducted for cement one in each flask. The optimum water:cement ratio for samples containing only cement was 0.35, which was determined by using the uniform mixing index (Hachmi *et al.* 1990) and later checked for the maximum value of the maturity factor (C_M), which can be expressed as:

$$C_M = \sqrt{\frac{Q_{\text{emax}}}{t_{e \text{ max}}}} \quad [11]$$

The optimum water:cement ratio required for an additive-cement mix was 0.35 plus an amount related to the ‘*apparent water absorption*’ of the cork granules. Generally, lightweight aggregates absorb most of the water within 30 min (Neville 1995). Keeping this in mind and in order to overcome the floating problem of cork, the ‘*apparent water absorption*’ was determined by stirring cork granules in water for 30 min and then removing the free surface water with a wet cloth. Subsequently, the moisture content of the cork granules was measured as the ‘*apparent water absorption*’ by oven drying at 105 °C. The ‘*apparent water absorption*’ for cork granules was 104% and for cork dust 202% by weight. These values were rounded to 100% and 200%, respectively, and were used for estimating the required water for each mix. These values appear to be high, but water absorptions of 80 and 300% have been reported for lightweight aggregates like pumice and vermiculite, respectively (Cheng and Lee 1986).

The hydration tests were performed in Dewar flasks. The hydration temperature of each mix was recorded with the help of thermocouples (T-type), which were connected to a computer-based data-recorder. A very similar system was used and described in detail by Irle and Simpson (1993). Samples for the hydration tests were prepared by thoroughly mixing cement and weighed oven-dried additive material in a plastic bag. The required amount of water was then added and mixed for two minutes. A T-type thermocouple was attached to the bag for measuring the temperature change of the mix. The plastic bag was then placed in a Dewar flask.

All the hydration experiments were carried out in a temperature controlled room at $20 \pm$

2°C. The cooling rate constant and heat capacities of the Dewar flasks were determined by measuring the cooling rates of 50 and 100 ml samples of hot water. The following relationships were used to calculate cooling rate constants for the various material combinations.

$$\frac{d(T_i - T_r)}{dt_i} = -k(T_i - T_r) \quad [12]$$

Where T_i is the temperature recorded at any time t_i and k is the cooling rate constant for any loading plus the Dewar flask. The value of k was obtained from the slope of the line generated by plotting the left hand term in equation [12] as an ordinate and the temperature rise ($T_i - T_r$) as an abscissa. Since the rate of heat loss of a Dewar flask remains constant whether empty or loaded and only the cooling rate changes with loading, cooling rate constants for two different loadings can be related as:

$$k_1(C_{c1} + C_f)(T_i - T_r) = k_2(C_{c2} + C_f)(T_i - T_r) \quad [13]$$

Where C_c is the heat capacity of the contents and C_f is the heat capacity of the Dewar flask. k_1 and k_2 are cooling rate constants at different loadings. The heat capacity of the contents is the sum of the heat capacities of the each constituent in the mix. The heat capacity of a constituent is obtained by multiplying its mass and specific heat. Thus, the total heat capacity of the contents can be calculated as:

$$C_c = \sum_{j=1}^{j=n} m_j c_j \quad [14]$$

Where, n is the total number of constituents in the mix, m_j and c_j are the mass and specific heat of the j th constituent in the mix. The specific heat values of cement, sand, cork and water are 0.84, 0.84, 1.8 and 4.184 J g⁻¹ K⁻¹ (0.2, 0.2, 0.43, and 1 cal g⁻¹ °C⁻¹), respectively (Incropera and DeWitt 1981; RILEM 1997).

The heat capacity (C_f) and cooling rate constant (k_f) of the empty Dewar flask were calculated from the following relationships:

$$C_f = \frac{(k_2 C_{c2} - k_1 C_{c1})}{k_1 - k_2} \quad [15]$$

$$k_f = \frac{k_1(C_{c1} + C_f)}{C_f} = \frac{k_2(C_{c2} + C_f)}{C_f} \quad [16]$$

The cooling constant (k_c) can then be calculated for any new loading and Dewar flask from the following equation:

$$k_c = \frac{k_f C_f}{C_c + C_f} \quad [17]$$

The rate of heat evolution (Q_i), at any instance t_i , was calculated from the following relationship:

$$Q_i = \frac{dH_i}{dt_i} = (C_c + C_f) \left(\frac{d(T_i - T_r)}{dt_i} + k(T_i - T_r) \right) \quad [18]$$

The total heat evolved up to any instance t_i was obtained by integrating the rate of heat evolution with respect to time:

$$H_i = (C_c + C_f) \left((T_i - T_r) + \sum_0^i k(T_i - T_r) dt \right) \quad [19]$$

The value for the heat of hydration using the maturity function (Q_e) was obtained by numerically differentiating the total heat with respect to both, the real time and the 'equivalent time', calculated using equation [9] at the reference temperature of 20 °C. The value of t_{max} was obtained from the rate of heat evolution curve based on 'equivalent time' as shown in Figure 2. The compatibility index (CI) was calculated using equation [10]. For comparison purposes, some of the indices given in Table 1, such as C_T , C_H and C_A , were also calculated. For determining the value of R_T , equation [3] in Table 1 was corrected for room temperature (T_r) and the following equation was used, because there appears to be a typographical error in the paper of Hachmi *et al.* (1990).

$$R_T = \left(\frac{T_{max} - T_r}{t_{max}} \right) \left(\frac{m_w + m_l}{m_c} \right) \quad [20]$$

All these indices were calculated for each replication and the mean value of the three replications of each composition is reported along with the coefficient of variation. For reporting, average heat evolution rate curves were drawn for each composition. For plotting the heat evolution rate curve with respect to the real time, a mean value of heat evolution rate of the three replications was calculated at each time interval. However, the values of heat evolution rate with respect to 'equivalent time' were not equal spaced for the three replications. Therefore, the data from the three replications was combined in each respective column of a spreadsheet and then sorted in order of increasing 'equivalent time'. Subsequently, the average heat evolution curve was plotted by using six point moving average for cement and three point moving average for other compositions.

Results and Discussion

The rate of heat evolution with respect to real time is shown in Figure 3 and with respect to 'equivalent age' or 'equivalent time' in Figure 4. The compatibility indices (CI_s) calculated from these results using equation [10] are compared in Table 2 with the indices determined by other methods. It is evident that high proportions of non-heat-generating components, such as sand and water, cause an unrealistic and excessive increase in the compatibility factor C_T . In the calculation of the C_T and C_H compatibility factors, the influence of the cooling rate is not recognised, which leads to inconsistencies. On the other hand, the C_A factor gives the gross heat generated over a specified period and does not reflect the intensity of the reaction. For instance, as can be seen in Figure 3, there is a considerable delay in the hydration of the mix containing 10% cork dust. However, the C_A factor still indicates 90% compatibility. The main reason for this is that most of the hydration in this mix takes place after 10 hours. Therefore, the total heat evolved might be similar to that of cement, but there is some considerable delay in the setting, which is important from a productivity point of view. While making cubes for compression tests the delay in setting was observed for the samples containing cork dust (Karade *et al.* 2003). Furthermore, it can be noticed that the values of the C_A factor given in Table 2 for cork granules, which are more or less equal for three compositions, do not reflect the hydration behaviour shown in Figure 3. In contrast, the CI index values reflect the hydration behaviour reasonably well. From Figure 3, it can be agreed that it is more desirable to make cork-cement composites from cork granules than from cork dust. However, the values of C_A for these compositions do not suggest this whereas the CI indices do.

From these results, it is evident that the proposed method describes the compatibility of these materials more consistently than other methods. However, the mix with 30% cork dust shows a slightly better compatibility than the mix with 20% cork dust. The cork dust is a fine waste from the industrial processing of cork and contains some mineral impurities (Karade *et al.* 2003). The high level of such impurities in the 30% mix may help to partially negate the retardation effect and hence explain the anomalous CI_s values. Such effects are not unusual and similar behaviour of cement due to the interference of certain metal salts is reported in the literature (Mehta and Monteiro 1993; Hills and Pollard 1997). However, this is a matter of further investigation, which is in progress.

Conclusion

The existing wood-cement compatibility assessment methods are useful tools for preliminary selection and comparison of various wood species. Most of these methods are based on T_{max} and t_{max} and use a low wood-cement ratio. One of the limitations of these methods is that they are effective only for the comparison of compatibility of different wood species when using the same wood:cement:water ratio and laboratory conditions. This is because they do not take into account the cooling rate and heat capacity of the system, which changes with a change in the mix ratio and weight. Moreover, due to a different heat capacity and varying retarding effects, the hydration proceeds at different temperatures, which further influences the values of T_{max} and t_{max} . Since the effect of varying hydration temperature on hydration rate is not a material property but rather varies with test conditions, this could lead to erroneous conclusions about compatibility.

The total heat produced within a certain time limit can be compared for different wood-cement mixes via the C_A factor. Many researchers have used this for assessing the wood-cement compatibility. In some cases, however, it may not be effective because it represents gross heat evolved rather than the intensity of hydration and therefore does not represent the true hydration behaviour. The proposed compatibility index (CI), which is developed in an attempt to overcome these problems, takes into consideration the heat capacity of the system, cooling rate, the varying temperature during the hydration process and intensity of the reaction. The initial results indicate that the values of CI reflect the hydration behaviour reasonably well. Although it cannot replace the testing by real manufacturing, it could help in understanding the role of various parameters on the hydration behaviour of the composite mix. However, more research in this area will help in standardising the test conditions and specifying the limits of acceptance for making wood-cement composites.

Acknowledgement

The first author is grateful to the Director, Central Building Research Institute (CSIR), Roorkee (India) for granting him study leave and to Buckinghamshire Chilterns University College, High Wycombe (UK) for providing financial support to undertake this study.

References

Ahn, W.Y. and A.A. Moslemi. 1980. SEM examination of wood-Portland cement bonds. *Wood Sci* .13(2), 77-82.

- Biblis, E.J. and C. LO. 1968. Sugar and other wood extractives: Effect on the setting of southern pine –cement mixes. *For. Prod. J.* 18(8), 28-34.
- Brandstetr, J., J. Polcer, J. Kratky, R. Holesinky and J. Havlica. 2001. Possibilities of the use of isoperibolic calorimetry for assessing the hydration behaviour of cementitious systems. *Cement Concrete Res.* 31, 941-947.
- Bruere, G.M. 1963. Importance of mixing sequence when using set-retarding agents with Portland cement. *Nature* 199(4888), 32-33.
- Carino, N.J. and H.S. Lew. 2001. The maturity method: From theory to application. In: *Proceedings of 2001 Structures Congress and Exposition*. May 21-23, Washington, D.C. American Society of Civil Engineers, Reston. pp. 1-19.
- Cheng, C.L. and M.K. LEE. 1986. Cryogenic insulating concrete—Cement based concrete with polystyrene beads. *ACI Journal* 83, 446-454.
- Coutts, R.S.P. 1988. Wood fibre reinforced composites. In: *Natural Fibre Reinforced Cement and Concrete*. Ed. R.N. Swamy. Blackie and Sons Ltd. Glasgow. pp.1-62.
- Dass, A. 1974. A simple method for determination of commercial suitability of timbers for Portland cement-bonded wood wool board. *IPIRI* 4(4), 161-164.
- Davies, G.W., M.D. Campbell and R.S.P. Coutts. 1981. A S.E.M. study of wood fibre reinforced cement composites. *Holzforschung* 35, 201-204.
- Demirbas, A. and A. Aslan. 1998. Effects of ground hazelnut shell, wood and tea waste on the mechanical properties of cement. *Cement Concrete Res.* 28(8), 1101-1104.
- Double, D.D. 1983. New developments in understanding the chemistry of cement hydration. *Phil. Trans. Roy. Soc. A.* 310, 53-66.
- Freiesleben Hansen, P. and J. Pedersen. 1977. Maturity computer for controlled curing and hardening of concrete. *Nordisk Betong* 1, 19-34.
- Hachmi, M. and A.A. Moslemi. 1989. Correlation between wood-cement compatibility and wood extractives. *For. Prod. J.* 39 (6), 55-58.
- Hachmi, M., A.A. Moslemi, and A.G. Campbell. 1990. A new technique to classify the compatibility of wood with cement. *Wood Sci. Technol.* 24(4), 345-354.
- Hermawan, D., B. Subiyanto and S. Kawai. 2001. Manufacture and properties of oil palm frond cement bonded board. *J. Wood Sc.* 47, 208-213.
- Hills, C.D. and S.J.T. Pollard. 1997. The influence of interference effects on the mechanical, microstructural and fixation characteristics of cement-solidified hazardous waste forms. *J. Haz. Mat.* 52, 171-191.

- Hofstrand, A.D., A.A. Moslemi and J.F. Garcia. 1984. Curing characteristics of wood particle from nine northern rocky mountain species mixed with Portland cement. *For. Prod. J.* 34 (2), 57-61.
- Hong, Z. and A.W.C. Lee. 1986. Compressive strength of cylindrical samples as an indicator of wood- cement compatibility. *For. Prod. J.* 36(11/12), 87-90.
- Incropera, F.P. and D.P. DeWitt. 1981. *Fundamentals of Heat Transfer*. John Wiley & Sons, New York. pp. 819.
- Irle, M. and H. Simpson. 1993. Agricultural residues for cement bonded composites. In: *Inorganic-bonded wood and Fibre Composite Materials*. Vol. 3. Ed. A.A. Moslemi. Forest Prod. Soc. pp. 54-58.
- Karade, S.R., M. Irle and K. Maher. 2003. Mechanical properties of cork cement composites.(To be published).
- Kjellsen, K.O. and R.J. Detwiler. 1992. Reaction kinetics of Portland cement mortars hydrated at different temperatures. *Cement Concrete Res.* 22(1), 112-120.
- Lawrence, C.D. 1998. Physicochemical and mechanical properties of Portland cements. *In: Lea's Chemistry of Cement and Concrete*, Ed. P.C. Hewlett. 4th ed. Arnold, London. pp 343-420.
- Lee, A.W.C., Z. Hong, D.R. Phillips and C.Y. Hse. 1987. Effect of cement/wood ratios and wood storage conditions on hydration temperature, hydration time, and compressive strength of wood-cement mixtures. *Wood Fiber Sci.* 19(3), 262-268.
- Mehta, P.K. and P.J.M. Monteiro. 1993. *Concrete: Structure, Properties and Materials*. 2nd Ed. Prentice Hall, Englewood Cliffs, NJ. pp. 548.
- Miller, D.P. and A.A. Moslemi. 1991a. Wood-cement composites: Effect of model compounds on hydration characteristics and tensile strength. *Wood Fiber Sci.* 23(4), 472-482.
- Miller, D.P. and A.A. Moslemi, A.A. 1991b. Wood-cement composites: species and heartwood-sapwood effects on hydration and tensile strength. *For. Prod. J.* 41(3), 9-14.
- Moslemi, A.A. 1999. Emerging technologies in mineral-bonded wood and fibre composites. *Advanced Performance Materials* 6, 161-179.
- Neville, A.M. 1995. *Properties of Concrete*. 4th ed. Prentice Hall, Harlow, UK. 844 pp.
- Odler, I. 1998. Hydration, setting and hardening of Portland cements. *In: Lea's Chemistry of Cement and Concrete*, Ed. P.C. Hewlett. 4th ed. Arnold, London. pp 241-297.
- prEN 196-9:1997. Methods of testing cement - Part 9: determination of heat of hydration - semi-adiabatic method (Draft). European Committee for Standardisation. Brussels. 23 pp.
- RILEM TCE 1. 1997. Adiabatic and semi-adiabatic calorimetry to determine the temperature increase in concrete due to hydration heat of the cement. *Mater. Struct.* 30, 451-457.

- Roskopf, P.A., F.J. Linton and R.B. Pepler. 1975. Effect of various accelerating chemical admixtures on setting and strength development of concrete. *JTEVA* 3(4), 322-330.
- Sandermann, W. and R. Kohler. 1964. Studies on mineral-bonded wood materials. IV. A short test of the aptitudes of woods for cement-bonded materials. *Holzforschung* 18, 53:59.
- Sandermann, W., H. Preusser and W. Schweers. 1960. The effect of wood extractives on the setting of cement-bonded wood materials. *Holzforschung* 14, 70-77.
- Semple, K.E., R.B. Cunningham and P.D. Evans. 1999. Cement hydration tests using wood flour may not predict the suitability of *Acacia mangium* and *Eucalyptus pellita* for the manufacture of wood-wool cement boards. *Holzforschung* 53, 327-332.
- Simatupang, M.H. 1979. Water requirement for the production of cement bonded particleboard. *Holz Roh Werkstoff*. 37(10), 379-82.
- Weatherwax, R.C. and H. Tarkow. 1964. Effect of wood on setting of Portland cement. *For. Prod. J.* 14(12), 567-570.
- Zhengtian, L. and A.A. Moslemi. 1986. Effect of western larch extractives on cement setting. *For. Prod. J.* 36(1), 53-54.

S.R. Karade¹⁾

M.A. Irle

K. Maher

Faculty of Technology,

Buckinghamshire Chilterns University College,

High Wycombe – HP11 2JZ

UK

Email: s.karade@bcuc.ac.uk, k.maher@bcuc.ac.uk

M.A. Irle

Present address:

Ecole Supérieure du Bois,

B.P. 10605 - Rue Christian Pauc,

44306 Nantes Cedex 3,

France

Email: mark.irle@ecolesuperieuredubois.com

1) Corresponding author

Table 1. Various methods of wood-cement compatibility assessment

Base	Classification Index	Equation	Equation no.	Wood:Cement:Water ratio	Reference
T_{max}	Suitable ($T_{max} > 60^{\circ}\text{C}$), Intermediately suitable ($T_{max} = 50$ to 60°C), Unsuitable ($T_{max} < 50^{\circ}\text{C}$).	---	-	20:200:100	Sanderman and Kohler (1964)
t_{max}	Inhibitory index (I) Low I value indicate good compatibility	$I = \left(\frac{t_{max} - t'_{max}}{t'_{max}} \right) 100$	[1]	15:200:90.5	Weatherwax and Tarkow (1964)
S	Inhibitory index (I) Low I value indicate good compatibility	$I = \left[\left(\frac{t_{max} - t'_{max}}{t'_{max}} \right) \left(\frac{T'_{max} - T_{max}}{T'_{max}} \right) \left(\frac{S' - S}{S'} \right) \right] 100$	[2]	15:200:90.5	Hofstrand <i>et al.</i> (1984)
T_{max} and t_{max}	Weighted Maximum Temperature ratio (C_T) High C_T value indicate good compatibility	$R_T = \frac{T_{max}}{t_{max}} \left(\frac{m_w + m_l}{m_c} \right)$	[3]	15:200:90.5	Hachmi <i>et al.</i> (1990)
		$C_T = \left(\frac{R_T}{R'_T} \right) 100$	[4]		
	Maximum Heat Rate Ratio (C_H) High C_H value indicate good compatibility	$R_H = \left(\frac{T_{max} - T_r}{t_{max}} \right) (mc_w + mc_l + mc_c + mc_d)$	[5]		Hachmi <i>et al.</i> (1990)
		$C_H = \left(\frac{R_H}{R'_H} \right) 100$	[6]		
H	Area ratio (C_A) Compatible ($C_A > 68\%$), Moderately compatible ($68\% < C_A < 28\%$) and Not compatible ($C_A < 28\%$)	$C_A = \left(\frac{A_{wc}}{A_{nc}} \right) 100$	[7]		Hachmi and Moslemi (1989); Hachmi <i>et al.</i> (1990)

Abbreviations (Apostrophe (') represents neat cement).

T_{max} = maximum temperature, t_{max} = time to reach T_{max} , S = slope of the time-temperature curve, H = heat of hydration, R_T = weighted maximum temperature, R_H and R'_H are maximum heat rate (J/h), A_{wc} and A_{nc} are areas under the hydration heat rate curve from 3.5 h to 24 h of wood-cement mix and cement respectively, mc_w , mc_l , mc_c and mc_d are thermal capacities in J/K of water, wood, cement and Dewar flask respectively; and T_r = room temperature.

Table 2. Comparison of compatibility indices assessed by various methods*

Material (by weight of cement)	Additive content (wt.%)	W/c ratio	C_I (Eqn. 9)	C_T (Eqn. 4 & 20)	C_H (Eqn. 5 & 6)	C_A (Eqn.7)
Cement	--	0.35	100 (2.62)	100 (12.15)	100 (14.34)	100 (14.94)
Sand	100	0.35	88 (6.96)	267 (9.90)	82 (15.38)	86 (8.33)
Cork	10	0.45	81 (0.71)	111 (4.97)	82 (4.45)	85 (8.52)
	20	0.55	68 (4.15)	113 (6.57)	66(11.61)	86 (13.77)
	30	0.65	53 (4.42)	88 (12.58)	46 (15.50)	86 (4.26)
Cork dust	10	0.55	58 (3.81)	65 (16.38)	45 (17.36)	90 (13.55)
	20	0.65	43 (2.53)	67 (10.02)	36 (11.71)	74 (2.36)
	30	0.95	44 (2.37)	121 (4.37)	57 (1.62)	73 (7.12)

* Coefficient of variation (%) is given in parenthesis

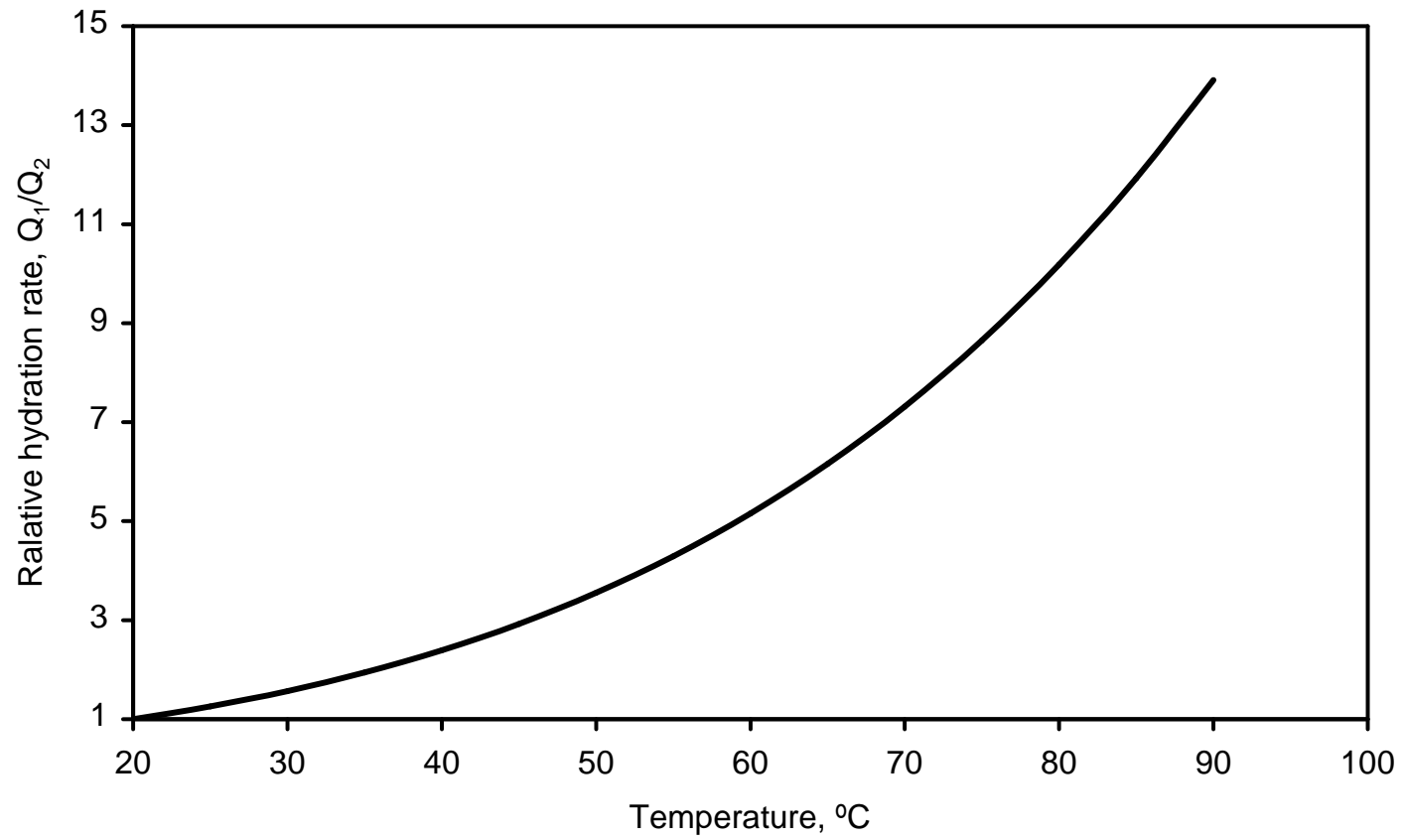


Fig. 1. Effect of temperature on the hydration rate of cement. Q_1 and Q_2 are the hydration rates at any temperature and at 20°C , respectively.

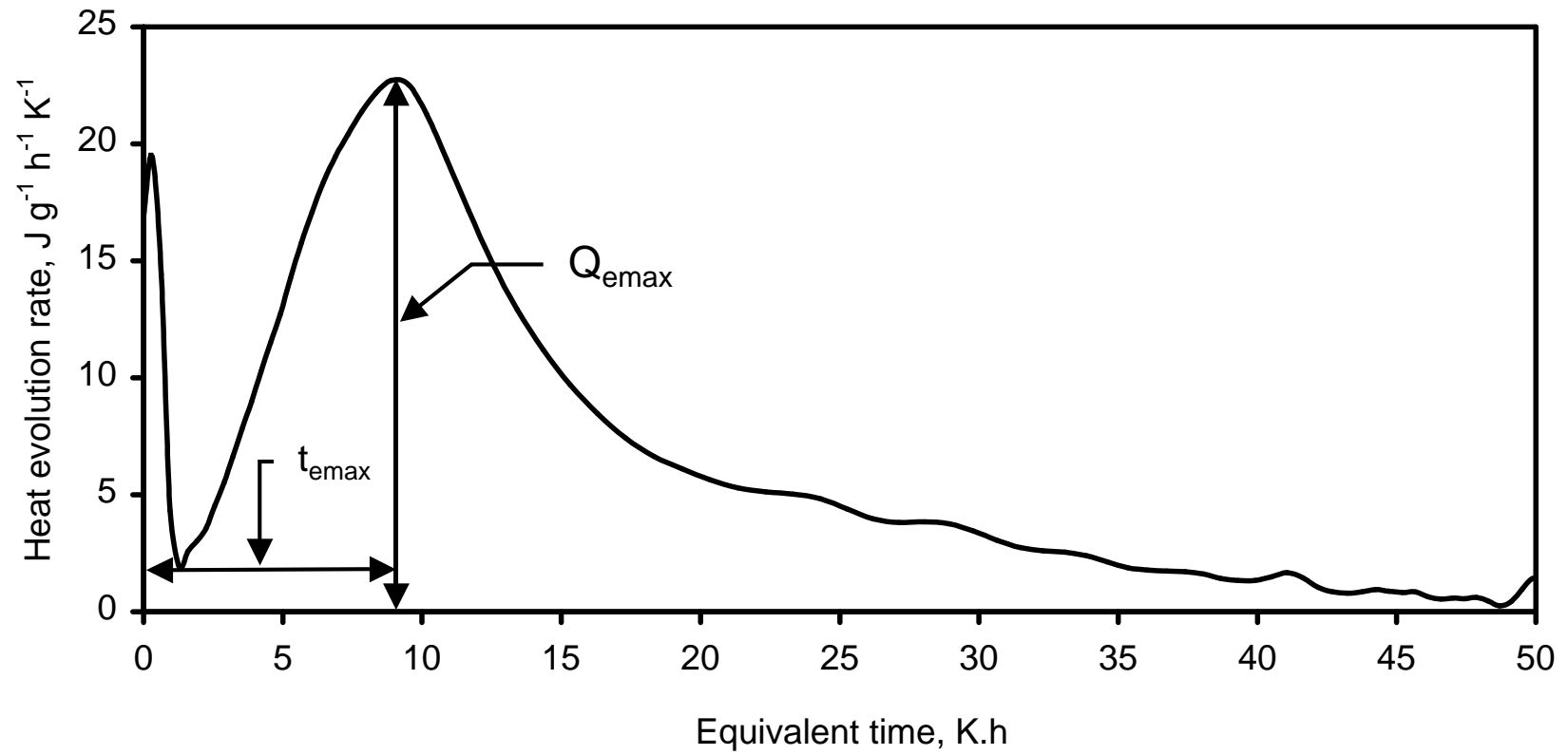


Fig. 2. A typical heat evolution curve based on a maturity function showing the determination of t_{emax} and Q_{emax} .

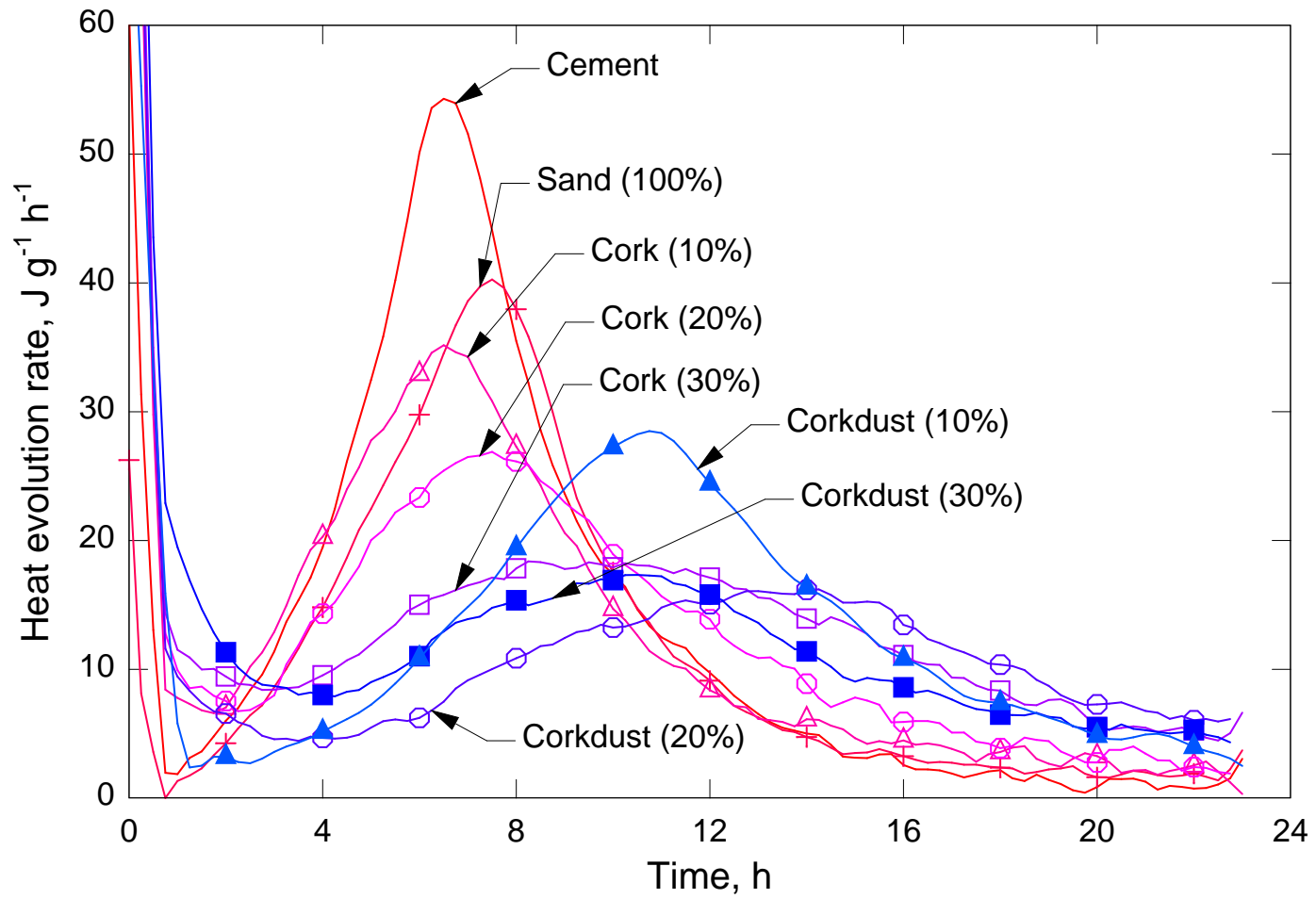


Fig. 3. Heat evolution rate with respect to real time.

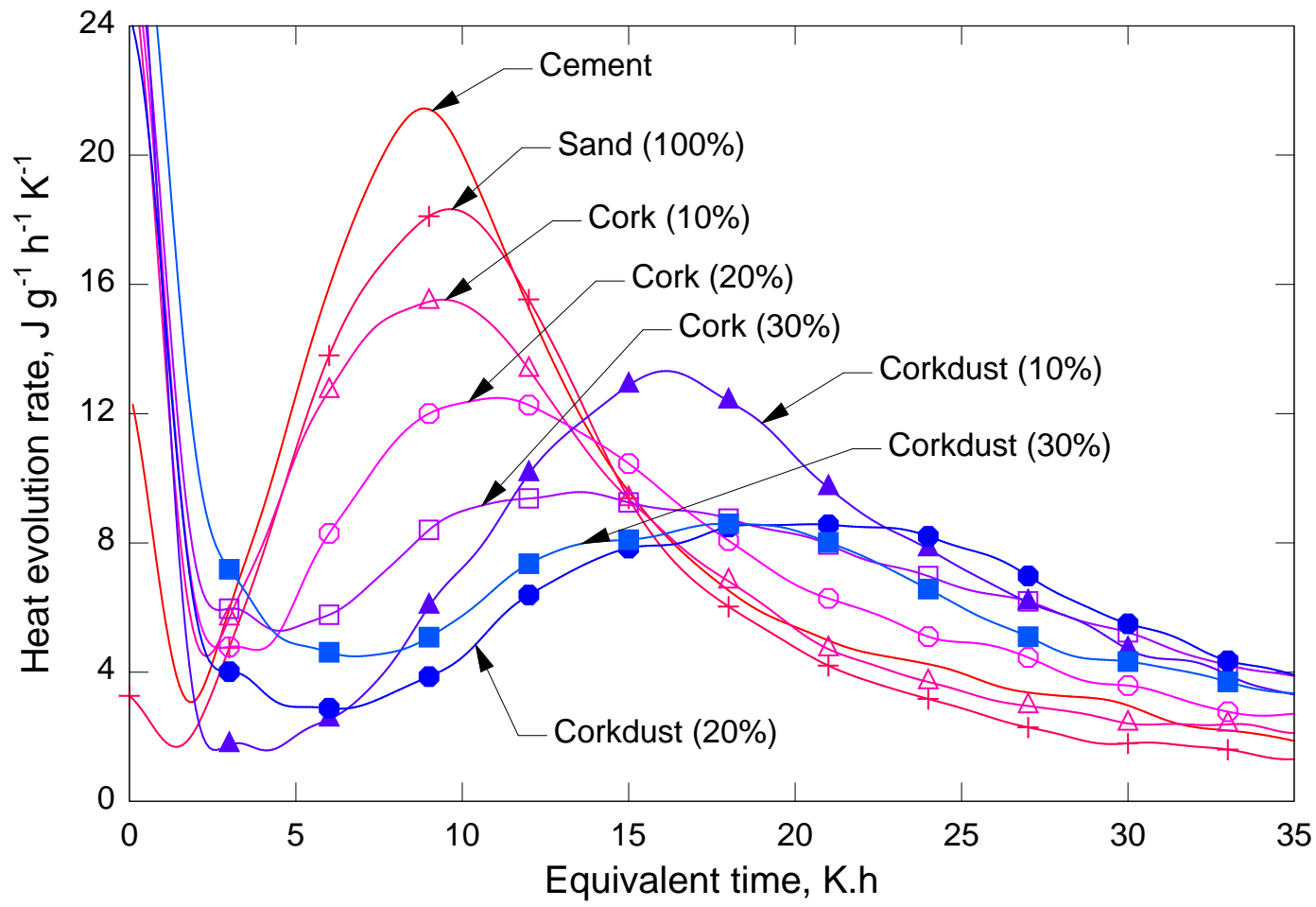


Fig. 4. Heat evolution rate measured using maturity function.