JOURNAL OF MATERIALS SCIENCE 33 (1998) 3601–3605

Improving the vibration damping capacity of cement

XULI FU, XIAOHUI LI, D. D. L CHUNG
Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA

Cement pastes containing latex (20–30% by weight of cement), methylcellulose (0.4–0.8% by weight of cement) and silica fume (15% by weight of cement, either as received or acid treated) were compared in terms of the dynamic flexural mechanical properties, as expressed by the loss tangent (damping capacity), storage modulus and loss modulus at 0.2–2 Hz (loading frequency) and 30–150 °C. Treated silica fume and latex are by far the most effective admixtures for enhancing the loss tangent (up to 0.18, an increase of up to 390%). Silica fume (whether as received or treated) is the most effective admixture for enhancing the storage modulus (up to 15 GPa). Latex tends to give a high loss modulus (up to 0.18 GPa) at 2 Hz; silica fume tends to give a high loss modulus (up to 2.2 GPa, an increase of up to 2200%) at 0.2 Hz. © *1998 Kluwer Academic Publishers*

1. Introduction

The dynamic mechanical properties of concrete have received much less attention than the static mechanical properties, in spite of the fact that dynamic loading conditions are commonly encountered in civil infrastructure systems. The dynamic loading can be due to live loads, sound, wind and earthquakes. Both elastic and anelastic properties are relevant, as the former pertains to the stiffness (as described by the storage modulus) and the latter pertains to the vibration damping capacity (as described by the loss tangent). The dynamic mechanical properties of concrete can be greatly affected by the admixtures [1, 2]. Moreover, they depend on the frequency of the loading and the temperature [2]. A systematic study of the dynamic properties requires testing at various combinations of frequency and temperature and comparing the properties of different concretes at the same combination of frequency and temperature. This paper provides a systematic study of cement pastes containing various additives.

Fu and Chung [2] have previously shown that certain additives can improve the vibration damping ability of cement paste, specifically latex (styrene butadiene) in the amount of 20% by weight of cement, methylcellulose in the amount of 0.4% by weight of cement and methylcellulose plus silica fume (0.4% by weight of cement for methylcellulose and 15% by weight of cement for silica fume). Latex was recommended for frequencies exceeding 1.5 Hz, and methylcellulose + silica fume was recommended for frequencies below 1.5 Hz. Fibres were not recommended [2]. This work extends the earlier work by studying the effect of latex in amounts of 25% and 30% by weight of cement, the effect of methylcellulose in amounts of 0.6% and 0.8% by weight of cement, and the effect of silica fume (with and without methylcellulose; with and without surface treatment). Thus, this work, together with the previous study, provides a comparative study of the effects of latex (in various amounts), methylcellulose (in various amounts), silica fume (with and without surface treatment), and methylcellulose + silica fume on the dynamic mechanical properties of cement paste.

Because of the importance of flexure in the dynamic loading of bridges and numerous other civil infrastructure components, this work addresses the dynamic mechanical properties under flexure. In particular, this paper provides a comparative study of the dynamic flexural properties of cement pastes containing various additives (latex, methylcellulose, silica fume and methylcellulose + silica fume) and at various combinations of temperature (30–150 °C) and frequency (0.2–2.0 Hz). The loss tangent, storage modulus and loss modulus (product of loss tangent and storage modulus) are reported for each combination of admixture, frequency and temperature. The loss tangent describes the damping capacity; the storage modulus describes the stiffness. The loss modulus is an important quantity, as it combines damping capacity and stiffness, as both high damping capacity and high stiffness are desired properties.

The additives used in this work for enhancing the vibration damping capacity of cement are also useful for improving other properties that are also important for structures. For example, latex-modified concrete is known for its increased bond strength, reduced permeability, decreased water absorption, increased resistance to freezing and thawing, increased flexural and tensile strengths, increased flexural toughness and improved abrasion resistance [3–12]. The addition of cellulose derivatives also helps the bonding [13–15]. The addition of silica fume to concrete is effective for increasing the compressive strength [16–19], decreasing the drying shrinkage [18, 19] increasing the abrasion resistance [20], increasing the bond strength with the reinforcing steel [21, 22] and decreasing the permeability [23]. Surface treatment of silica fume with sulphuric acid prior to incorporation in a cement matrix results in composites exhibiting increases in tensile strength, modulus, ductility and abrasion resistance, relative to the values obtained by using as-received silica fume [24].

2. Experimental methods

2.1. Materials

Cement paste made from portland cement (type I) from Lafarge Corporation (Southfield, MI) was used from the cementitious material. The additives used include firstly latex, a styrene butadiene polymer dispersion (Dow Chemical Co., Midland, MI; 460NA) with the polymer particles making up about 48% of the dispersion and with styrene and butadiene in the weight ratio 66 : 34, such that the latex (20%, 25% or 30% by weight of cement) was used together with an antifoam (Dow Corning Corporation, Midland, MI; number 2410; 0.5% by weight of latex), secondly methylcellulose (Dow Chemical Corporation; A15-LV; 0.4% by weight of cement), which was dissolved in water and used together with a defoamer (Colloids Inc., Marietta, GA; Colloids 1010; 0.13 vol%) and thirdly silica fume (Elkem Materials Inc., Pittsburgh, PA; number 965; 15% by weight of cement; either as received or after surface treatment by immersing in sulphuric acid (96%) for 2 h, washing with water and then drying at 150 °C for 1–2 days). The water reducing agent was a sodium salt of a condensed naphthalenesulphonic acid (Tamol SN, Rohm and Haas Company, Philadelphia, PA) used in amounts as shown in Table I for the various mixes. Table I also shows the water–cement ratio for each mix. The amounts in Table I were chosen in order to maintain the slump at around 170 mm. No aggregate (whether fine or coarse) was used.

A Hobart mixer with a flat beater was used for mixing. For the case of cement pastes containing latex, the latex and antifoam were first mixed by hand for about 1 min. Then this mixture, cement and water were mixed in the Hobart mixer for 5 min. For the case of pastes containing methylcellulose, methylcellulose was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Then this mixture, cement and water were mixed in the Hobart mixer for 5 min. After pouring the mix into oiled moulds, an external vibrator was used to decrease the amount of air bubbles. The specimens were demoulded after 1 day and then allowed to cure at room temperature in air (relative humidity, 40%) for 28 days. Mechanical testing was performed at 28 days.

TABLE I Amounts of water and water-reducing agent (WR) for each mix. L, latex; M, methylcellulose; SF, silica fume

	Water-to-cement ratio	WR-to-cement ratio (%)
Plain	0.45	0
+ L	0.23	0
+ M	0.32	1
+ SF	0.35	3
+ M + SF	0.35	3

2.2. Testing procedure

Dynamic mechanical testing (ASTM Standard D 4065-94) at controlled frequencies (0.20, 1.00 and 2.00 Hz) and temperatures (25–150 °C) were conducted under flexure using a Perkin–Elmer Corporation model DMA 7E dynamic mechanical analyser. Measurements of tan δ (loss tangent) and storage modulus were made simultaneously as a function of temperature at various constant frequencies. The heating rate was 2 °C min^{-1}, which was selected to prevent any artificial damping peaks which may be caused by higher heating rates. The specimens were in the form of beams (24 mm × 8 mm × 3 mm) under three-point bending, such that the span was 20 mm. The loads used were all large enough that the amplitude of the specimen deflection was always over the minimum value of 5 μm required by the equipment for accurate results. The loads were set so that each different type of specimen was always tested at its appropriate stress level. Six specimens of each type were tested.

3. Results and discussion

Tables II–IV show the loss tangent, storage modulus and loss modulus, respectively, of various cement pastes at 28 days for various combinations of temperature and frequency. The loss tangent is enhanced by any of the admixtures, with the greatest loss tangent provided by treated silica fume at 0.2 Hz and by latex in the amount of 30% by weight of cement at 2 Hz. The treated silica fume is much more effective than as-received silica fume in increasing the loss tangent. The loss tangent increases with increasing latex or methylcellulose amount. However, even at a latex amount of 20% by weight of cement, the loss tangent is larger than those corresponding to any of the other admixtures (except treated silica fume) for most combinations of frequency and temperature, especially at 90 °C and below. As the temperature increases, the advantage of latex over as-received silica fume diminishes. In particular, at 90 °C and 0.2 Hz, the loss tangent for as-received silica fume exceeds that for latex in the amount of 20% by weight of cement. Because of the small amount of methylcellulose (0.4–0.8% by weight of cement) compared with latex (20–30% by weight of cement), methylcellulose is much less effective than latex in enhancing the loss tangent. However methylcellulose + as-received silica fume is comparable with latex (in the amount of 20% by weight of cement) in the ability to enhance the loss tangent at 120–150 °C and 1.0 Hz. Moreover, methylcellulose + as-received silica fume is better than as-received silica fume in the

TABLE II Loss tangent, tan δ (± 0.002), of various cement pastes at various temperatures and frequencies, here the highest value for each combination of temperature and frequency is shown in bold type: L, latex; M, methylcellulose; SF, as-received silica fume; SF′, treated silica fume; the latex-to-cement ratio is shown in parentheses after L; the methylcellulose-to-cement ratio is shown in parentheses after M

	tan δ														
	30 °C			60 °C			90 °C			120 °C			150 °C		
	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
1 Plain	0.035	$< 10^{-4}$	$< 10^{-4}$	0.044	$< 10^{-4}$	$< 10^{-4}$	0.051	$< 10^{-4}$	$< 10^{-4}$	0.053	$< 10^{-4}$	$< 10^{-4}$	0.054	$< 10^{-4}$	$< 10^{-4}$
2 + L (0.20)	0.122	0.075	0.045	0.118	0.066	0.028	0.107	0.068	0.018	0.105	0.062	0.016	0.110	0.060	0.018
3 + L (0.25)	0.135	0.093	0.062	0.130	0.087	0.047	0.125	0.082	0.027	0.121	0.078	0.029	0.126	0.075	0.029
4 + L (0.30)	0.142	**0.112**	**0.069**	0.139	**0.096**	**0.054**	0.131	**0.088**	**0.036**	0.129	0.084	**0.034**	0.133	0.081	**0.034**
5 + M(0.4%)	0.073	0.005	$< 10^{-4}$	0.081	0.008	$< 10^{-4}$	0.071	0.008	$< 10^{-4}$	0.070	0.011	$< 10^{-4}$	0.068	0.015	$< 10^{-4}$
6 + M(0.6%)	0.086	0.018	$< 10^{-4}$	0.092	0.022	$< 10^{-4}$	0.084	0.023	$< 10^{-4}$	0.083	0.025	$< 10^{-4}$	0.081	0.028	$< 10^{-4}$
7 + M (0.8%)	0.104	0.031	0.005	0.102	0.035	0.007	0.096	0.036	0.012	0.097	0.038	0.008	0.093	0.042	0.015
8 + SF	0.107	$< 10^{-4}$	$< 10^{-4}$	0.112	$< 10^{-4}$	$< 10^{-4}$	0.123	$< 10^{-4}$	$< 10^{-4}$	0.121	$< 10^{-4}$	$< 10^{-4}$	0.109	$< 10^{-4}$	$< 10^{-4}$
9 + M (0.4%) + SF	0.105	0.035	$< 10^{-4}$	0.105	0.043	$< 10^{-4}$	0.120	0.051	$< 10^{-4}$	0.120	0.063	$< 10^{-4}$	0.120	0.061	$< 10^{-4}$
10 + SF′	**0.172**	0.091	$< 10^{-4}$	**0.161**	0.093	$< 10^{-4}$	**0.182**	0.084	$< 10^{-4}$	**0.175**	**0.091**	$< 10^{-4}$	**0.168**	**0.087**	$< 10^{-4}$

TABLE III Storage modulus (± 0.02) of various cement pastes at various temperatures and frequencies, where the highest value for each combination of temperature and frequency is shown in bold type: L, latex; M, methylcellulose; SF, as-received silica fume; SF′, treated silica fume; the latex-to-cement ratio is shown in parentheses after L; the methylcellulose-to-cement ratio is shown in parentheses after M

	Storage modulus (GPa)														
	30 °C			60 °C			90 °C			120 °C			150 °C		
	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
1 Plain	1.91	2.05	1.96	1.92	2.01	1.94	1.94	1.99	1.95	1.86	1.96	1.93	1.90	1.92	1.91
2 + L (0.20)	2.75	2.22	2.38	2.48	2.02	2.06	2.35	2.44	2.07	2.25	2.14	2.08	2.20	2.20	2.08
3 + L (0.25)	2.97	2.45	2.48	2.71	2.21	2.29	2.58	2.32	2.31	2.49	2.37	2.32	2.41	2.45	2.34
4 + L (0.30)	3.12	2.57	2.61	2.87	2.33	2.41	2.74	2.44	2.43	2.63	2.49	2.45	2.58	2.57	2.46
5 + M (0.4%)	4.12	4.95	4.83	4.17	4.75	4.75	4.37	4.68	4.68	4.33	4.63	4.62	4.37	4.53	4.52
6 + M (0.6%)	4.32	5.15	5.04	4.38	4.96	4.97	4.58	4.89	4.89	4.56	4.85	4.87	4.58	4.75	4.74
7 + M (0.8%)	4.53	5.26	5.28	4.59	5.18	5.19	4.79	5.06	5.09	4.78	5.08	4.09	4.79	4.96	4.98
8 + SF	5.76	6.93	6.97	5.70	6.65	6.73	5.68	6.43	6.51	5.63	6.05	6.18	5.78	5.78	5.92
9 + M (0.4%) + SF	6.20	6.90	6.85	5.75	6.42	6.41	5.65	6.01	6.01	5.31	5.82	5.81	5.35	5.80	5.78
10 + SF′	**11.29**	**15.02**	**11.65**	**11.92**	**14.52**	**11.74**	**12.28**	**13.67**	**11.57**	**10.99**	**13.30**	**11.24**	**10.78**	**12.66**	**11.06**

TABLE IV Loss modulus (±0.02) of various cement pastes at various temperatures and frequencies, where the highest value for each combination of temperature and frequency is shown in bold type: L, latex; M, methylcellulose; SF, as-received silica fume; SF′, treated silica fume; the latex-to-cement ratio is shown in parentheses after L; the methylcellulose-to-cement ratio is shown in parentheses after M

	Loss modulus (GPa)														
	30 °C			60 °C			90 °C			120 °C			150 °C		
	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
1 Plain	0.067	0.000	0.000	0.085	0.000	0.000	0.099	0.000	0.000	0.099	0.000	0.000	0.103	0.000	0.000
2 + L (0.20)	0.336	0.167	0.107	0.293	0.133	0.058	0.251	0.141	0.037	0.236	0.133	0.033	0.242	0.132	0.037
3 + L (0.25)	0.401	0.228	0.154	0.352	0.192	0.108	0.323	0.190	0.062	0.301	0.185	0.067	0.304	0.184	0.068
4 + L (0.30)	0.443	0.288	**0.180**	0.399	0.224	**0.130**	0.359	0.215	**0.088**	0.339	0.209	**0.083**	0.343	0.208	**0.084**
5 + M (0.4%)	0.301	0.025	0.000	0.338	0.038	0.000	0.310	0.037	0.000	0.303	0.051	0.000	0.297	0.068	0.000
6 + M (0.6%)	0.372	0.093	0.000	0.403	0.109	0.000	0.385	0.112	0.000	0.378	0.121	0.000	0.371	0.133	0.000
7 + M (0.8%)	0.471	0.163	0.026	0.468	0.181	0.036	0.460	0.182	0.061	0.464	0.193	0.033	0.445	0.208	0.075
8 + SF	0.616	0.000	0.000	0.638	0.000	0.000	0.699	0.000	0.000	0.681	0.000	0.000	0.630	0.000	0.000
9 + M + SF	0.651	0.242	0.000	0.604	0.276	0.000	0.678	0.307	0.000	0.637	0.367	0.000	0.642	0.354	0.000
10 + SF′	**1.94**	**1.37**	0.000	**1.92**	**1.35**	0.000	**2.23**	**1.15**	0.000	**1.92**	**1.21**	0.000	**1.81**	**1.10**	0.000

ability to enhance the loss tangent at 1.0 Hz and any of the temperatures, although it is similar to as-received silica fume at 0.2 Hz. Hence, the addition of methylcellulose to a mix with as-received silica fume serves to increase the loss tangent at high frequencies (i.e., 1 Hz). Roughly, the overall trend is that the loss tangent decreases in the order: treated silica fume, latex, methylcellulose + as-received silica fume, as-received silica fume and methylcellulose.

The storage modulus is enhanced by any of the admixtures, with the greatest storage modulus provided by treated silica fume for all combinations of frequency and temperature. The treated silica fume is much more effective than as-received silica fume in increasing the storage modulus. Methylcellulose is less effective than as-received silica fume in enhancing the storage modulus. Methylcellulose + as-received silica fume is much better than methylcellulose and slightly worse than as-received silica fume in the ability to enhance the storage modulus, except that methylcellulose + as-received silica fume is better than as-received silica fume at (i) 0.2 Hz and 30 °C, (ii) 0.2 Hz and 60 °C and (iii) 1.0 Hz and 150 °C. Latex in any of the three amounts is less effective than methylcellulose in enhancing the storage modulus, in spite of the small amount of methylcellulose. The storage modulus increases with increasing latex or methylcellulose amount for any combination of frequency and temperature.

The loss modulus is enhanced by any of the admixtures, with the greatest loss modulus provided by treated silica fume at 0.2 and 1.0 Hz and by latex (30% by weight of cement) at 2.0 Hz. Methylcellulose + as-received silica fume is quite effective (but not the most effective) at 1 Hz. Methylcellulose is much less effective than as-received silica fume in enhancing the storage modulus, although methylcellulose + as-received silica fume is comparable with as-received silica fume at 0.2 Hz and better than as-received silica fume at 1.0 Hz. Latex (30% by weight of cement) is not as good as methylcellulose (0.8% by weight of cement) at 0.2 Hz for enhancing the loss modulus but is better than methylcellulose (0.8% by weight of cement) at 1–2 Hz. The loss modulus increases with increasing latex or methylcellulose amount for any combination of frequency and temperature. The high loss modulus associated with latex is due to the high loss tangent, whereas that associated with silica fume, methylcellulose or methylcellulose + silica fume is due to the high storage modulus.

The high loss tangent of cement pastes with latex or methylcellulose is due to viscoelastic damping provided by the latex. The amount of viscoelastic phase governs the extent of viscoelastic damping. The high loss tangent of cement pastes with treated silica fume indicates that filler–matrix interface slippage is also effective in providing damping to cement pastes. However, the filler (i.e., silica fume) is more effective than a polymer (i.e., latex or methylcellulose) in enhancing the storage modulus.

That methylcellulose provides a much higher storage modulus than latex, in spite of its small amount, is probably due to the differences in the degree of dispersion of the polymer and in the polymer–cement bonding. Methylcellulose is a liquid solution whereas latex is a dispersion when added to the mix. As a result, methylcellulose may be better dispersed than latex.

Treated silica fume and latex are by far the best admixtures for enhancing the damping capacity, whereas silica fume (whether as received or treated) is the best admixture for enhancing the storage modulus. The loss modulus is a figure of merit that describes the damping capacity combined with the storage modulus. Latex tends to give a high loss modulus at a high frequency (2 Hz); silica fume tends to give a high loss modulus at a low frequency (0.2 Hz).

4. Conclusion

Cement pastes containing latex (20–30% by weight of cement), methylcellulose (0.4–0.8% by weight of cement) and silica fume (15% by weight of cement, either as received or acid treated) were compared in terms of the dynamic flexural mechanical properties, as expressed by the loss tangent (damping capacity), storage modulus and loss modulus at 0.2–2 Hz (loading frequency) and 30–150 °C. Treated silica fume and latex are by far the most effective admixtures for enhancing the loss tangent (up to 0.18, an increase of up to 390%). Silica fume (whether as received or treated) is the most effective admixture for enhancing the storage modulus (up to 15 GPa). Latex tends to give a high loss modulus (up to 0.18 GPa) at 2 Hz; silica fume tends to give a high loss modulus (up to 2.2 GPa, an increase of up to 2200%) at 0.2 Hz. Methylcellulose provides a much higher storage modulus than latex, in spite of its small amount. The storage and loss moduli increase with increasing latex or methylcellulose amount. The loss tangent decreases in the order: treated silica fume, latex, methylcellulose + as-received silica fume, as-received silica fume, and methylcellulose.

References

1. N. MOISEEV, *Proc. SPIE* **1619** (1992) pp. 192–202.
2. X. FU and D. D. L CHUNG, *Cem. Concr. Res.* **26** (1996) 69.
3. ACI Committee 548, *ACI Mater. J.* **91** (1994) 511.
4. D. G. WALTERS, *Transportation Res. Record* **1204** (1988) 71.
5. *Idem.*, ACI Mater. J. **87** (1990) 371.
6. L. A. KUHLMANN, *Int. J. Cem. Compos. Lightweight Concr.* **7** (1985) 241.
7. *Idem.*, *ACI Mater. J.* **87** (1990) 387.
8. Y. OHAMA, *ibid.* **84** (1987) 511.
9. P. MASLOW, "Chemical materials for construction" (McGraw-Hill, New York, 1982) pp. 341–364.
10. P. CHEN, X. FU and D. D. L. CHUNG, *Cem. Concr. Res.* **25** (1995) 491 .
11. X. FU and D. D. L. CHUNG, *ibid.* **27** (1997) 643.
12. P. SOROUSHIAN and A. TLILI, in Proceedings of the Symposium on Polymer-Modified Hydraulic–Cement Mixtures and Mortars, ASTM Special Technical Publication, 1176 (American Society for Testing and Materials, Philadelphia, PA, 1993) pp. 104–119.
13. P. CHEN, X. FU and D. D. L. CHUNG, *Cem. Concr. Res.* **25** (1995) 491.
14. K. H. KHAYAT, *ACI Mater. J.* **93** (1996) 134.
15. K. HAYAKAWA and T. SOSHIRODA, in Proceedings of the International Symposium on Adhesion Between Polymers and Concrete, RILEM Technical Committee **52** (1986) pp. 22–31. Chapman & Hall, London, Engl. and New York, NY, U.S.A.
16. B. B. SABIR, *Mag. Concr. Res.* **47** (1995) 219.
17. H. A. TOUTANJI and T. EL-KORCHI, *Cem. Concr. Aggregates* **18** (1996) 78.
18. M. N. HAQUE, *Cem. Concr. Compos.* **18** (1996) 333.
19. P. CHEN and D. D. L. CHUNG, *Composites* **24** (1993) 33.
20. Z. SHI and D. D. L. CHUNG, *Cem. Concr. Res.* **27** (1997) 1149.
21. T. A. BURGE, "Bond in concrete", edited by P. Bartos (Applied Science, London, 1982) pp. 273–281.
22. O. E. GJORV, P. J. M. MONTEIRO and P. K. MEHTA, *ACI Mater. J.* **87** (1990) 573.
23. J. G. CABRERA and P. A. CLAISSE, *Cem. Concr. Compos.* **12** (1990) 157.
24. XIAOHUI LI and D. D. L. CHUNG, *Cem. Concr. Res.* **28** (1998) 493.

Received 20 June 1997
and accepted 11 May 1998