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Optimization of Moulding Technology of Polymer Concrete Used for Manufacture Precision Tool Machine Bases

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Abstract

Aspects of moulding technology have a great effect on the mechanical properties and curing behaviour of polymer concrete used to manufacture the base of precision tool machine. In this paper, the results and the analysis are both presented of an experimental investigation on the effects of moulding technology on polymer concrete (PC) used for manufacture the base of precision tool machine. Effect of voids population on compressive strength of polymer concrete was examined. Various frequencies were applied during the packing operation of the polymer concrete samples using the vibration table. The optimum frequency for vibration and for producing a PC sample with the highest compressive strength was found to be 18.9375 Hz, which resulted in 109 MPa compressive strength for basalt, sand and chalk composition. In addition influence of Dimethyl aniline (DMA) amount and moulding temperature on mixing process and the strength of matrix domain were experimented. The relation between time of viscosity build-up t (min), temperature T (°C) and DMA content C (%) were correlated. This relation was used to obtain the suitable time required for mixing to prevent the mixing while the polymeric binder reach the gelling time through the copolymerization process. Also mixing technology and its influence on mechanical properties of PC were investigated. The optimized mixing technology was reached. Enhancing certain aspects of moulding technology could lead to an elevation of the mechanical strength of PC that may assist in producing polymer concrete with a high level of compliance with the optimisation criteria for PC used in manufacturing bases for precision tool machinery.

Keywords: Polymer concrete; Resin binder; DMA; Precession tool machine bases; Mixing technology; Compressive strength; Void; Temperature; Time

Introduction

Polymer concrete (PC) is a composite material consisting of well-graded inorganic aggregates bound using a resin instead of the water and cement binder typically used in traditional cement concretes [1,2]. Unsaturated polyester resins (UPEs) are thermosetting materials used as the binding matrix in PCs [1,3-7]. UPEs cure via radical copolymerization of a monomer, such as methyl methacrylate (MMA), and the low molecular weight unsaturated polyester liquid when an initiator and an accelerator are added at ambient conditions [8-12]. The mixture viscosity increases during the exothermic curing process until a solid three-dimensional cross-linked polymer network is formed [9,13,14]. The good chemical resistance and mechanical properties of the resin and its adhesion to aggregates in PC are the main advantages that the application of PC in precision tool machine bases [15] and other applications [5,16], where PCs are used due to their high damping properties and their ability to absorb system unwanted vibrations [16]. Several strategies to improve UPE properties are studied in the literature. When a rubbery phase is introduced into a polymeric matrix, the mobility of the rubber molecules enhances the vibration energy dissipation in the resin [17,18]. Literature suggests that varying the resin curing rate via curing temperature [19] or initiation mechanism or post curing heat treatment of the resin have affected UPE damping properties [20]. Curing and processing conditions also have studied the effect of high temperature curing and post curing heat treatment on the microheterogeneity of UPE and its effect on its mechanical properties. Sanchez et al. [21] showed that the styrene ratio in UPE pre-polymerization mixture affects phase continuity of resin after curing due to the limited miscibility of polystyrene in UPE. This phase separation can be affected dramatically by curing temperature [22]. The main purpose of this study is to optimize the moulding technology for polymer concrete used for producing the base of precision tool machine. This was achieved through experimenting DMA (promoter) amount, moulding temperature and mixing process and their effect on mechanical properties of polymer concrete and the polymeric matrix. Also manufacturing conditions of PC, including low initial viscosity of UPE resin to obtain good wetting of aggregate particles during the initial mixing process were consider.

Experimental Section

Materials

UPE resin is made from commercial unsaturated polyester AROPOL (67% unsaturated polyester dissolved in 33% styrene) obtained from Huntsman Chemical Company (Australia), methyl methacrylate (MMA) from Degussa (Australia), cobalt octoate and Dimethyl aniline (DMA) from Alfa Aesar (USA), and methyl ethyl kenton peroxide (MEKP) NR20 from Nuplex Industries (Australia). The basalt, river gravel, sand, and chalk used as aggregates were from Roca. Fly ash was from Cement Independent Australia and spodumene from Talison Minerals, Western Australia.

Specimen preparation

A typical resin sample was produced by mixing a volumetric 3:2 ratio of UP to MMA. To this mixture, 0.8% cobalt octoate (promoter), 0.2% DMA (accelerator) and 2% (v/v) MEKP (initiator) were added and mixed respectively. The mixture was cast in high density

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polyethylene (HDPE) mould and cured in ambient conditions for 24 hours. Polymer concrete sample produced by mixing the resin with aggregate and left for 28 days to cure. Aggregate preparation begins with the preparation of the appropriate amount of each aggregate. In these samples, 70% basalt, 30% sand and 10% of fly ash was used. The overall aggregate volume fraction was 83% and the remainder was resin. All the aggregates were kept for three hours inside the vacuum chamber to reduce the moisture content to approximately zero. During this process, the temperature in the vacuum chamber reached 160°C.

Kinetics

Brookfield RVDV-II+Pro viscometer (USA) was used to determine the copolymerization mixture viscosity during the reaction. The reaction mixture temperature profile was measured using a thermocouple (SE00 type K thermocouple, Pico technology, UK).

Method of monitoring resin temperature profile during polymerisation

The procedure begins by setting the temperature of the Brookfield circulating bath using a digital controller TC-102 for 25°C with a wait of 10 minutes to obtain thermal equilibrium. The resin is prepared and poured in the PET tube, then immersed in the bath and held by a holder. A thermocouple sensor (SE00 type K thermocouple, Pico technology, UK) is placed in the resin and connected to the Pico data accusation system containing a TC-08 thermocouple data logger (Pico technology, UK) and connected to a computer to display the temperature profile. The resin temperature through the polymerisation was measured using the following equipment:

- Brookfield circulating bath with digital controller TC-102
- Tube holder, tube 50 ml.
- Thermocouple sensor (SE00 type K thermocouple, Pico technology, UK).
- Pico data accusation system contain TC-08 thermocouple data logger (Pico technology, UK) Computer for data collection.

Mechanical measurements

The three points bending flexural test was carried out on resin samples using Zwick Z010 (Germany) to evaluate tensile and flexural strength. The specimens dimensions were 50 mm × 10 mm × 2.5 mm. Zwick 3130/3131 (Germany) was used to measure. For tensile testing Zwick 3130/3131 (Germany) was used, a sample is inserted in both jaws of the universal testing machine at the center of the jaws in a vertical orientation. The cross sectional dimensions of the sample are measured using a dial caliper and the dimensions are then entered into the testXpertII software available on the computer connected to the universal machine. The cross-head speed is 25 mm/min, since once the set-up is accomplished, initiating the test by the mechanical by the computer software. Once the specimen has failed, the stress-elongation curve can be obtained and tensile stress derived using testXpertII software.

Experimental setup for measuring the frequency and the amplitude of a vibrating table

Three accelerometers were mounted on the vibration table which was (manufactured by Bennett equipment in South Australia) to capture the frequency and the amplitude in three directions of X, Y and Z. Figure 1 illustrates the experiment set up to measure frequency and amplitude of the vibration table. The data acquisition system model SCI-1000, made in Hungary by National Instruments, which feeds the data to the computer to be analysed using data interface software (Lab view). Figure 1 shows the accelerometers, vibration table, data acquisition system and the computer with Lab view on. The measurement of the frequency and the amplitudes starts when the mould in mounted on the vibrating table and the accelerometer captures the movements. The accelerometer converts the sample movements to a voltage signal that is amplified for transfer to the data acquisition system. It is then converted into a digital signal using a DAQ data card National Instrument, USA. The computer receives a digital signal to be analysed by software signal analysis, which presents the data in the time domain or frequency domain as required.

Result and Discussion

The effect of the number of voids on the compressive strength of polymer concrete

Voids can affect the mechanical properties of PC and a high number of them are not desirable. Reducing the voids population can enhance the mechanical properties of the concrete [23] as the microstructure and location of voids have a negative effect on mechanical strength. They can also influence the cracks that emanate and propagate, resulting in failure of the composite material [24]. In order to reduce the number of voids, a vibration table was used to induce a high level of compaction for PC. There is a range of frequencies available on a vibration table that used for achieving high level of aggregates compaction in PC. Each frequency induces a specific level of compaction on a PC sample which has a direct influence on mechanical properties. To find the optimum frequency, PC samples were prepared using various frequencies during the compaction stage and were tested for compressive strength. The PC sample with the highest compressive strength is the one with the lowest voids population and the optimum compaction. The frequency controller of a vibration table starts at 0 Hz and finishes with 50 Hz. The measuring of the frequency and amplitudes starts at 0 and goes up to 32 Hz. When 32 Hz is reached, the accelerometer magnetic attachment will not remain attached to the vibration table and falls down. Table 1 shows the result measurement of frequency and the amplitude of the vibrating table. The direction of oscillation does not seem to have an effect on the value of frequencies, as shown in Figure 2. As the frequency increases, the amplitude increases, particularly in

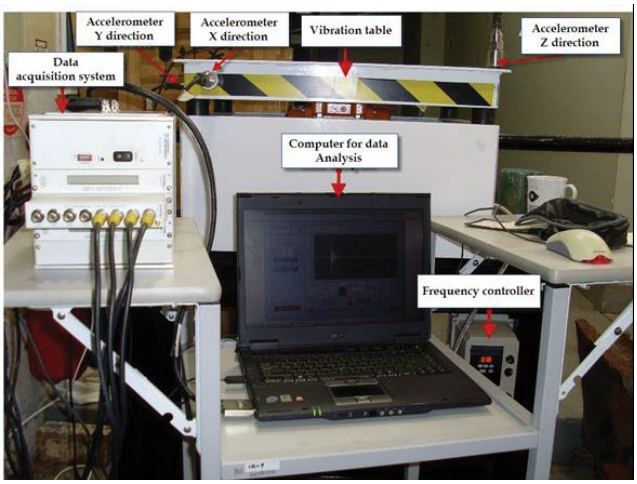

Figure 1: Experimental step for measuring the frequency and the amplitude of a vibrating table.

Z direction for frequencies more than 30 Hz, as shown in Figure 2. Different frequencies were applied during the packing operation of the PC samples using the vibration table.

The mould containing the PC sample was fixed on to the vibration table and vibration applied to the PC sample as shown in Figure 3. When the liquid resin reached the surface of the PC sample in the cylindrical mould and the bubbles stopped coming out of the surface resin, the vibration table was stopped. The PC sample was then left for 28 days to cure at the ambient temperature. Upon completion of curing, the compressive strength was tested for each (Table 1).

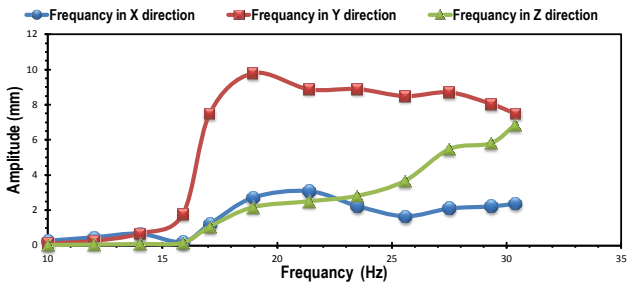

Figure 2: Relation between the amplitude and set frequency for the vibration table.

Figure 3: The mould contains the PC sample mounted on vibration table, the frequency applied for compaction.

Method for determination of the compressive strength of a concrete specimen PC sample according to Australian standard AS 1002.9 – 1986 "Method of testing concrete: Part 9". The optimum frequency for vibration and for producing a PC sample with the highest compressive strength was found to be 18.9375 Hz (20 Hz by the vibration table switch controller), which resulted in 109 MPa compressive shown in Table 2.

Identification of maximum moulding duration as a function of moulding temperature and DMA content in resin binder

Moulding time is the time required to mix PC with aggregates, then pour the PC mixture into the mould and vibrate the mould using a vibration table until the vibration process finished. The Dimethyl aniline DMA (promoter) amounts, MEKP initiator, monomer reactivity ratio and moulding temperature are the key controls of resin rheological behaviour from the commencement of mixing aggregates with the resin to the end of the final operation in vibrating the mould. In addition the DMA (promoter) amount affects the mechanical and rheological properties of the resin [25] and hence has an effect on the PC composite's mechanical properties. During the moulding time the resin is required to be in a liquid state. This enhances the wetting of the aggregate particles, improves the mixing operation and increases particle settlement to achieve good mixing and compaction. As a result there is a reduction in the number of voids. The overall result is the enhancement of the mechanical properties of PC. To achieve such a result, it is important to identify the DMA amount required correlate with the moulding temperature, and the moulding time. Extending the moulding time up to gel stage could cause some damage such as crack initiation during the compaction process ,or result in a low level of mixing, both leading to reduced mechanical properties of PC.

Effect of DMA (promoter) contents on temperature rise during curing

The effect of the DMA content on temperature rise during curing was investigated. DMA content exerts an influence on the temperature of resins during their curing. Resins without DMA did not exhibit any recordable rise of temperature while resins with DMA had temperature increases up to 120°C for 0.3% of accelerator. The increase of DMA content leads to an increase in the exothermic maximum resin temperature during the curing and shortens the time needed for a temperature rise, as shown in Figure 4. The method of measuring temperature was described in experimental section.

Vibrating table control reading	Frequency in X direction Hz	Amplitude in X direction mm	Frequency in Y direction Hz	Amplitude in Y direction mm	Frequency in Z direction Hz	Amplitude in Z direction mm
10	10	0.256	10	0.11	10	0.02
12	12	0.45	12	0.263	12	0.047
14	14	0.66	14	0.672	14	0.08
16	15.875	0.188	15.88	1.767	15.875	0.147
18	17.062	1.21	17.06	7.5	17.062	1.067
20	18.9375	2.7169	18.94	9.8	18.9375	2.162
22	21.375	3.097	21.38	8.888	21.375	2.5
24	23.5	2.24	23.5	8.9	23.5	2.814
26	25.56	1.66	25.56	8.5	25.56	3.66
28	27.5	2.7	27.5	8.71	27.5	5.4637
30	29.312	1.0189	29.31	8.06	29.312	5.8
32	30.375	0.766	30.38	7.499	30.375	13.853

Table 1: The frequency and amplitude of the vibrating table.

Effect of DMA contents on viscosity growth during resin copolymerization

The effect of DMA on the curing rate was investigated by increasing the initial content of 0.001 DMA in 40% ARAPOL/60% MMA resin composition and adding more DMA to the mixture. The addition of DMA increases the initial viscosity of the mixture in the curing process. The amount of DMA was varied from 0.001 to 0.003, causing an increase of the viscosity growth rate, as shown in Figure 5. The method used to measure viscosity was described experimental section.

Varying the DMA content is another measure that is used to demonstrate the effect of DMA content on the time required for the resin to reach the maximum viscosity as shown in Figure 5. An increase in the DMA content and the moulding temperature decrease the time required for the resin maximum viscosity to be reached, as shown in Figure 6.

The time required for the resin to reach maximum viscosity is essential knowledge when manufacturing bases for precision tool machinery. The reason is both the PC mixing and the moulding tasks should be accomplished prior to maximum viscosity being reached by the resin binder (640 cP), which is on the verge of the gel point. A drastic increase in viscosity hinders mixing, resulting in PC material not to be mixed and moulded efficiently. The effect of both temperature and DMA amount will combined in a convergence on the PC base's

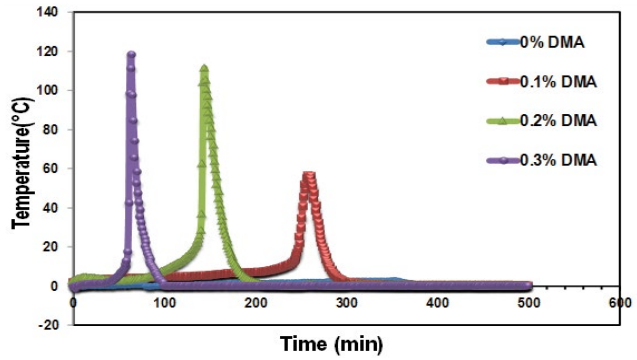

Figure 4: Temperature of MMA/ARAPOL resins with different content of DMA.

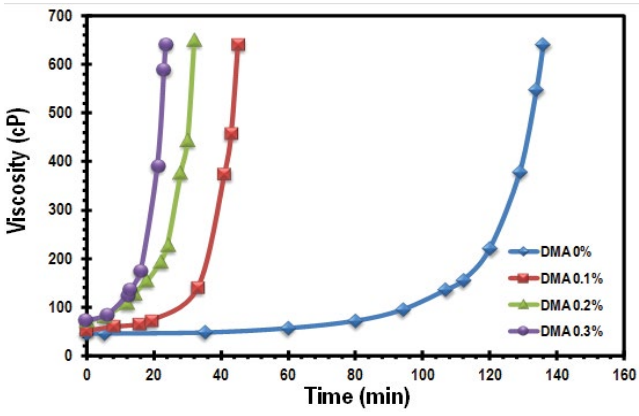

Figure 5: Viscosity of resins versus their curing time for a variety of DMA content.

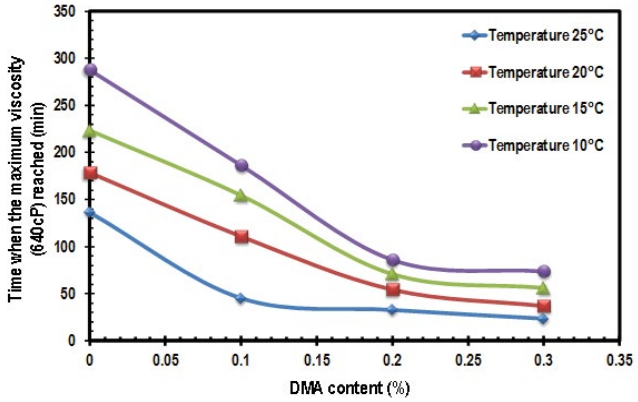

Figure 6: Time to the maximum temperature of 40% ARAPOL/60% MMA resins with different contents of DMA for various moulding temperatures.

mechanical properties and curing behaviour. The relation between time of viscosity build-up t (min), temperature T (°C) and DMA content C (%) can be described in the following empirical equation:

$$\ell nt = 6.42\text{-}5.1C\text{-}0.069T$$

Using the above equation, the DMA amount was calculated which is compatible with the known moulding temperature, as illustrated in Table 3. The recommended DMA content for various moulding temperatures in Table 3 can be validated by using Figure 6. For example, the recommended DMA for 10°C moulding temperature is 0.27%. In Figure 6 the time required to reach the maximum measurable viscosity (640 cP) is 73 minutes at 10°C and 0.3% DMA. When DMA is reduced, the time for reaching the maximum viscosity increases at a particular temperature. This indicates that the time for reaching the maximum viscosity is greater than 73 minutes when the DMA amount is less than 0.3% at 10°C, the time considered when the DAM amount calculated for Table 3 is 75 minutes approximately. The required time for moulding is 40-50 minutes, depending on the size of the PC base and the complexity of the design. The recommended DAM correlated with temperature in Table 3 provides 15-35% extra time to the required time as an extra precaution to guarantee that the moulding operation. takes place when the resin is at the low viscosity level. This is to avoid reaching the verge of gel time, especially during compaction stage that may initiate undesirable micro-cracks in the polymeric matrix that can propagate during the solidification of the base, since UPE resin has high shrinkage compared to epoxy (Table 3).

Effect of DMA contents on resin binder mechanical properties

The effect of DMA on the resin's mechanical properties was investigated using flexural strength, tensile strength and elongation. The method of measuring flexural strength and tensile strength testing was described in experimental section. Tensile strength, flexural strength and elongation all decreased with an increase in DMA content, as illustrated in Table 4. Thus the strength of resins with 0.3% DMA is 25% lower than resins without DMA. Elongation is also reduced by 18% and these results are in partial agreement with those of Ganglani et al. [26]. This is attributed to the formation of micro-cracks, possibly caused by the excessive exothermal reaction in the presence of the accelerator as the exothermic reaction peak temperature increased as DMA amounts increase as shown in Figure 4. This caused non uniformed temperature distribution across the resin sample and initiate non uniform shrinkage when the resins solidify. It should be noted that this effect may be much

greater with larger volumes of resin, because of the scale factor. Taking into account the very low fraction of resin (the micro-layer thickness between aggregates) in PC composite material and the substantial heat exchange between the matrix and the fillers, the detrimental effect of DMA on mechanical properties to be much lower (Table 4).

Optimization of mixing technology of PC

The main purpose of concrete mixing is to achieve a uniform mixing of all materials [27]. Mixing technology is an important parameter for a PC with low binder content. Poorly mixed PC not only fails to meet the requirements for workability but also affects the PC's mechanical properties. Three mixing technologies were investigated for a specific aggregate composition (basalt, sand, flay ash). The first mixing technology (MT1) started by mixing the fine aggregate with 75% of the resin, followed by the medium-sized aggregate and then, finally, the coarse aggregate was added to the main mixture with the rest of the resin. The second mixing technology (MT2) began by mixing 20% of the resin with coarse aggregate. The micro-filler was separately mixed with 30% of resin and then added to the coarse aggregate resin mixture. The rest of the resin was separately mixed with the medium-sized aggregate and then mixed with the main mixture. In the third mixing technology (MT3), all aggregates were premixed and then mixed with the resin. A traditional concrete mixer was used to mix the PC for all the mixing technologies. A time of 15 minutes was used for all three mixing technologies. Samples to measure flexural strength were prepared for each mixing technology. A four-point flexural strength test was conducted according to the Australian standard AS1012.11-2000 method of testing concrete. The method used to test flexural strength was described in experimental section. Table 5 shows the flexural strength for all mixing methods. MT1 proved to be the most effective for basalt, sand and fly ash, and flexural strength reached the maximum of 22.6 MPa (Table 5).

Conclusions

This paper has examined aspects of moulding technology. Each has a different effect and influences the mechanical properties and curing behaviour of polymer concrete by various means. The optimum frequency when operating the vibration table to prepare a PC sample is identified as 18.9375 Hz. With this frequency, the PC samples produced the highest compressive strength. An empirical relationship connecting the moulding temperature and the DMA content was obtained using rheological analysis of the resin with various amount of DMA. A table showing moulding temperatures in the range of 8-30°C with DMA amounts in the range of 0-0.3% was constructed. It was found that increasing the DMA fraction in the resin binder has a slightly negative impact on the mechanical properties and increases the curing rate as well as the exothermic temperature profile. Various mixing technologies were investigated in order to obtain one that produces the PC with the highest flexural strength. It was found that MT1 produces a PC sample with 22.53 MPa, which is the maximum flexural strength.

Set frequencies on vibration table controller, Hz	Vibration time (min)	Frequency Measured, X direction (Hz)	Compressive strength (MPa)
16	10	15.875	98
18	12	17.062	93.5
20	16	18.9375	109
22	15	21.375	106
24	22	23.5	97
26	20	25.56	81

Table 2: Vibrating time and compressive strength of PC samples.

T, °C	8	9	10	11	12	13	14	15	16	17	18
DMA, %	0.3	0.29	0.27	0.26	0.25	0.23	0.22	0.21	0.19	0.18	0.17
T, °C	20	21	22	23	24	25	26	27	28	29	30
DMA, %	0.14	0.13	0.11	0.10	0.09	0.07	0.06	0.04	0.03	0.02	0.0

Table 3: Recommended DMA content for different moulding temperatures.

DMA content, %.	0	0.1	0.2	0.3
Modulus of Elasticity, MP	759	705	798	675
Tensile Strength, MPa	60.2	58.6	51.9	43.6
Elongation, %	10.1	9.3	8.1	8.3
Flexural strength	130	128.2	119.3	109.5

Table 4: Mechanical properties of resins with different volume fractions of DMA.

Mixing technology	Composition	Flextural Strength (MPa)
MT1	Basalt, Sand, Fly Ash	22.6
MT2	Basalt, Sand, Fly Ash	19.23
MT3	Basalt, Sand, Fly Ash	20.32

Table 5: Effect of mixing technology on flexural strength of PC.

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