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Time-Temperature Properties of Polymer Concrete Using Recycled PET

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Abstract

Recycled polyethylene terephthalate (PET) plastic waste can be chemically modified to produce unsaturated polyester. If properly formulated, the unsaturated polyester can be mixed with gravel, sand and fly ash to produce good quality polymer concrete (PC). The use of recycled PET can help reduce the cost of PC products, save energy, and allow the long term disposal of PET waste. The time and temperature dependent properties of PC using an unsaturated polyester resin based on recycled PET have been evaluated in this paper. Properties investigated include the effect of age on strength, the effect of temperature on strength and modulus, shrinkage and exotherm, thermal expansion and creep. These properties should provide useful information on the potential use of the PC in precast applications.

INTRODUCTION

Polymer concrete (PC) is made of inorganic aggregates bonded together by a resin binder. The material is strong, durable and cures fast. One common binder used in PC is unsaturated polyester, because of its relatively low cost and good properties compared to other resin binders.

A recent survey ranked precast products as important potential uses of PC.[1] Great needs for PC precast components are in utility components (vaults, junction boxes, trench lines, floor drains), building panels, transportation related components (median barriers, bridge panels, railroad ties, tunnel liners), high voltage insulators and flooring.[1,2] In all these applications, the time and temperature dependent properties of the PC might be important. The objective of this paper is, therefore, the report on the time and temperature dependent properties of PC using an unsaturated polyester resin based on recycled polyethylene terephthalate (PET) to enable the safe and appropriate use of the material in various precast applications.

RESEARCH SIGNIFICANCE

The high cost of the resin binder makes PC relatively expensive compared to Portland cement based materials. Recycled PET, mainly recovered from used beverage bottles, can be chemically modified to produce unsaturated polyester resins.[3] If the unsaturated polyester based on recycled PET is properly formulated, it can be mixed with inorganic aggregates to produce PC with very good mechanical properties.[4] The use of PC using unsaturated polyester resins based on recycled PET may help reduce the cost of PC products, save energy and alleviate a solid waste problem posed by plastics.

MATERIALS

The production of the unsaturated polyester resin based on recycled PET was done in two steps.[4] The first step consisted of digesting the PET molecules by charging the PET scrap and a glycol into a reactor and heating for several hours in the presence of a transesterification catalyst. The second step consisted of adding dibasic acids to the solution to produce the polyester resin. The unsaturated polyester was then diluted with styrene to reduce its viscosity and allow its further cure to a solid (polymer) upon the addition of suitable free radical initiators and promoters. Curing took place because the styrene combined with the reactive double bonds of the polyester chains, thus linking them together and forming a strong three-dimensional polymer network.[4]

The unsaturated polyester resin used in this study had a low viscosity of 110 cps at 25°C. The excellent wetting properties of the resin made it possible to formulate a PC system with a high aggregate–resin ratio. A high aggregate–resin ratio is not only important for economy (since less resin — the expensive component — is used), but also because it improves the properties and dimensional stability of the material. About 25% by weight of recycled PET was used in the production of the final resin. The resin was dark in color, since the recycled PET used in its production was not purified to the same extent as the recycled PET used in other applications, which should facilitate the recycling operation and minimize its cost (it should be noted that the most expensive part of the PET bottles recycling process is the removal of aluminium and paper impurities, and green and brown colors). The recycling of PET in PC will also allow the long term disposal of the PET waste — an important advantage in recycling applications.

The following coarse and fine inorganic aggregates were used in the experimental study: 10 mm pea gravel; Colorado river siliceous sand with a fineness modulus of 3·25 and ASTM Type F fly ash. The mineral fillers, except for fly ash which was obtained dry from the supplier, were oven-dried for a minimum of 24 h at 130°C to reduce their moisture content to less than 0·5% by weight, thus ensuring good bond between the polymer matrix and the inorganic aggregates. The aggregates were then cooled at room temperature and stored in closed containers.

The PC mixing procedure followed Polymer Concrete Test Method 1·0, of the Society of Plastics Industry; referred to as SPI 1·0.[5] The PC mix design was optimized for workability, strength and economy. The optimum mix design, proportioned by weight, was as follows: 10% resin, 45% oven-dried coarse aggregates, 32% oven-dried sand and 13% fly ash. The use of fly ash greatly improved the workability of the fresh PC mix. The fine and spherical particles of fly ash provided the fresh mix with better lubricating properties, thus improving its plasticity and cohesiveness. The better graduation obtained with fly ash also resulted in a hardened material with improved strength and mechanical properties. One per cent (by weight of resin) of 9% active oxygen methyl ethyl ketone peroxide initiator and 0·1% (by weight of resin) of 12% solution cobalt naphthenate (CoNp) promoter (used as an accelerator) were added to the resin immediately prior to its mixing with the inorganic aggregates to start the curing process. Mixing was done using a conventional concrete mixer for a period of about 3 min. Specimens were then cast in molds, vibrated, cured and then tested at room temperature, unless otherwise specified.

TESTING

There are no standard tests that are directly applicable to PC specimens. Therefore, ASTM standards developed for cement based materials were used as guidelines whenever applicable. The age at testing of the specimens was three days, unless otherwise specified. The properties presented in this paper represent the average of three specimens, unless otherwise noted.

The compressive strength of PC was determined on 75 × 150 mm compression cylinders that were tested at a constant loading rate of 45 kN min^{-1}. Small specimens were used because of the high strength of the PC. The strains were measured by means of electrical strain gages that were longitudinally bonded to the specimens at mid-height and connected to a data acquisition system. The flexural strength of PC was obtained by using 50 × 50 × 305 mm beams that were tested in third-point loading at a uniform rate of 2 kN min^{-1}. A dial gage was used to read the midspan deflection of the beams.

Shrinkage testing did not follow ASTM guidelines applicable to Portland cement concrete because the shrinkage mechanism in PC is different than in Portland cement-based materials. Therefore, a special device, shown in Fig. 1, was used to continuously monitor the shrinkage strain and peak exotherm of the PC. Specimens consisted of 75 × 75 × 305 mm beams cast inside Teflon-lined molds. The molds were wrapped in a plastic sheet that acted as an insulator to reduce the effect of ambient temperature changes on the plastic shrinkage readings. Immediately after mixing and placing the materials in the molds, the shrinkage measuring device was carefully inserted into the fresh PC mix. The shrinkage device consisted of a horizontal rod to which two removable angles were attached. One angle was fixed

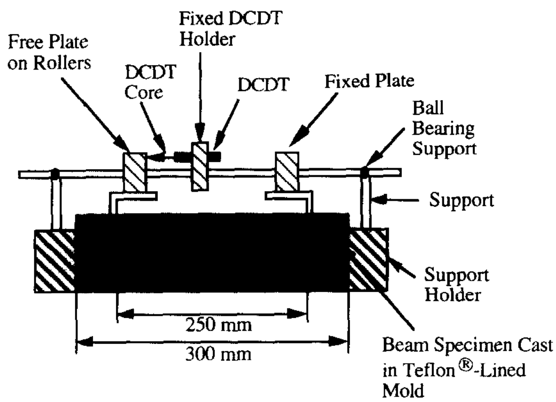

Fig. 1. PC shrinkage test.

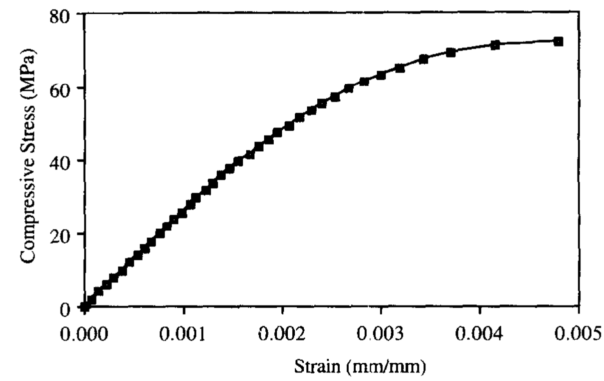

Fig. 2. Typical stress–strain curve in compression.

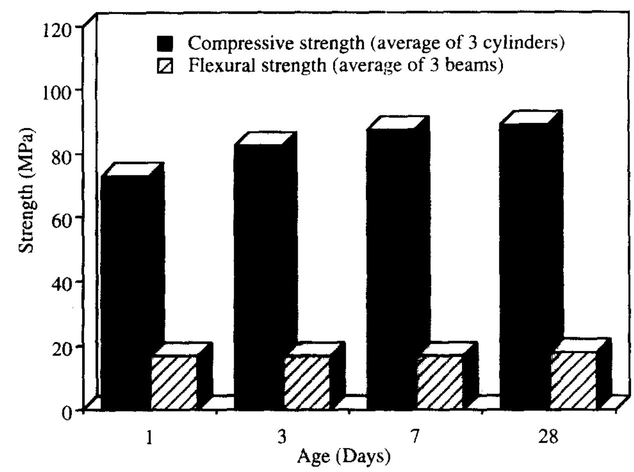

Fig. 3. Age effect on strength.

while the other was free to move on roller bearings. A direct current differential transformer (DCDT), attached to the rod, was used to record the longitudinal displacement induced by shrinkage.

The thermal expansion test used 75 × 150 mm cylinders. Longitudinal electrical strain gages were bonded to the specimens using a special epoxy system insensitive to high temperatures. The strain gages were then connected to a switch and balance unit in a full-bridge configuration. Strain and temperature readings were taken in increments of 6°C. The specimens were left at a constant temperature for a minimum of 8 h to ensure thermal stabilization before recording strains and temperatures.

Creep specimens consisted of 75 × 150 mm PC cylinders tested in uniaxial compression using a hydraulic spring-loaded creep frame. A constant stress, corresponding to a stress intensity ratio of 20% (which is the ratio of the applied compressive stress to the ultimate compressive strength), was applied to the specimens for a period of three months. During testing, cylinders were aligned on top of each other to ensure uniform stress in all of them. Four electrical gages were bonded to the specimens at mid-height, using epoxy, and then connected to an automated data acquisition system in a full-bridge configuration. Two gages were aligned longitudinally on opposite sides while the other two were aligned circumferentially on opposite sides. Electrical strain gages were also attached to dummy or control specimens that were left unloaded to correct for non-creep-related deformations such as shrinkage of the adhesive used to attach the strain gages, springs decompression in the loading frame, or ambient temperature changes. Since minor temperature changes could significantly affect the creep readings, the specimens were enclosed in an insulating Styrofoam box to ensure that the temperature was maintained at 25°C throughout the testing period.

RESULTS AND DISCUSSION

The typical compressive stress–strain curve for the PC is shown in Fig. 2. The stress–strain behavior of the PC is comparable to the one obtained with PC using virgin resins.[6] It can also be observed that the ultimate compressive strength and strain of PC are about two–three times larger than those corresponding to Portland cement concrete. At failure, the PC shattered violently and the remaining core of the cylinders had either a cone shape or a near vertical failure surface. The relatively high modulus of the PC makes the material suitable for use in precast applications.

The effect of age on the compressive and flexural strength of PC is shown in Fig. 3. PC achieves more than 80% of its final strength in one day. Conversely, normal cement concrete usually achieves about 20% of its final strength in one day. The early strength gain is important in precast applications because it permits the structures to resist large stresses early due to transportation and erection operations. The good compressive and flexural strength of PC allows the use of thinner sections in precast components, thus reducing dead loads in structures and minimizing transportation and erection costs.

The effect of temperature on the compressive and flexural strength of PC is shown in Fig. 4. Fillers and mixing utensils were placed in an environmental chamber at the desired temperature 48 h prior to mixing. After mixing, specimens were again put in an environmental chamber at the desired temperature for a period of one month prior to testing. Selected temperatures were −10, 25 and 60°C. Actual testing, performed at room temperature, was done immediately after removing the specimens from the environmental chamber. An increase in temperature results in loss in strength in the PC because the resin binder decreases in strength with an increase in temperature. For example, an increase in temperature from 25 to 60°C decreases the compressive strength by about 40%. The same kind of behavior was observed when PC using 100% virgin resin was tested.[7] PC is much more susceptible to high temperatures than normal cement concrete because the synthetic viscoelastic resin binder used in producing PC is more temperature-sensitive than the inorganic cement binder used in producing normal cement concrete. However, despite this loss in strength, PC remains at least twice as strong as Portland cement concrete, especially in flexure.

The effect of temperature on the compression and flexural modulus of PC is shown in Fig. 5. A decrease in modulus can be observed with an increase in temperature because of the viscoelastic properties of PC. The decrease in modulus is negligible when the temperature increases from −10 to 25°C. However, a decrease in modulus ranging from 35 to 40% is noted when the temperature increases from 25 to 60°C.

The typical shrinkage-exotherm curve for the PC is shown in Fig. 6. It can be observed in the figure that most of the shrinkage in PC occurs within the first 8 h after mixing and stops after 24 h. It is also noted in the figure that most of the shrinkage takes place after the occurrence of the peak exotherm. PC only experiences short term shrinkage (plastic shrinkage) due to resin polymerization, whereas cement-based materials experience both short term shrinkage (plastic shrinkage) and long term shrinkage (drying shrinkage) due to water evaporation from the cement paste. In precast components, low shrinkage is important because excessive shrinkage strains may significantly affect the dimension of these structures, thus making their demolding, assembly, or use, more difficult.

The typical thermal expansion for the PC is shown in Fig. 7. The coefficient of thermal expansion for the PC, obtained from the figure, is about $15 \times 10^{-6}{}^{\circ}C^{-1}$. The coefficient of the thermal expansion of PC is at least twice as high as the one corresponding to Portland cement concrete. This

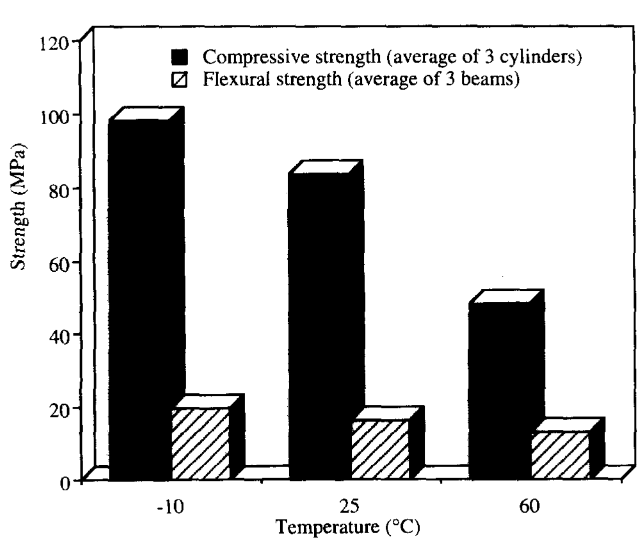

Fig. 4. Temperature effect on strength.

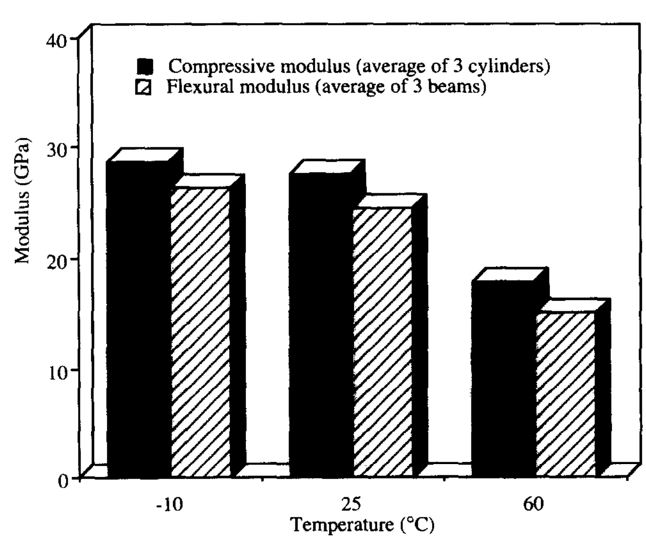

Fig. 5. Temperature effect on modulus.

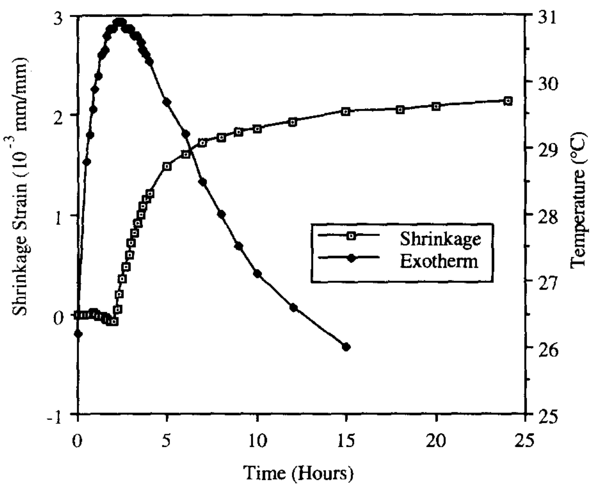

Fig. 6. Typical shrinkage and exotherm.

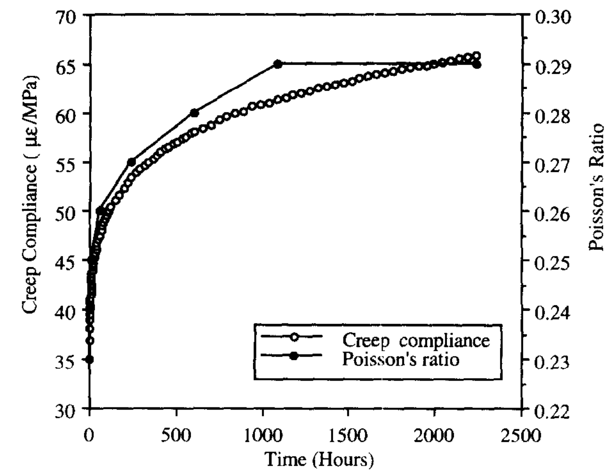

Fig. 8. Typical creep compliance and Poisson's ratio versus time.

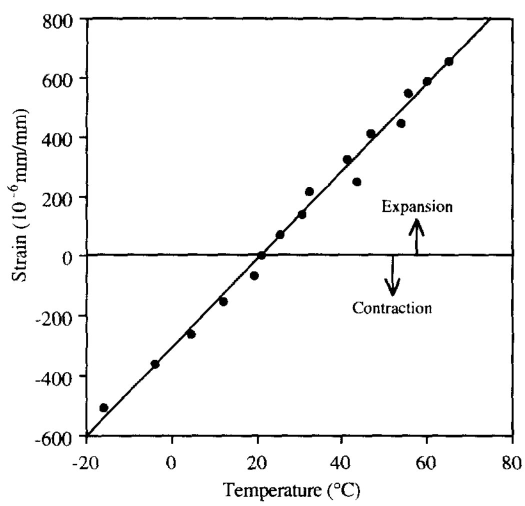

Fig. 7. Typical thermal expansion.

relatively high thermal expansion of the PC should be accounted for during the design of construction joints in PC walls or slabs. Also, special precautions should be taken when using PC in conjunction with Portland cement concrete or steel to produce composite structures. Changes in temperature in the composite structures may create relatively high shear stresses at the interface between the two materials because of the difference in the coefficient of thermal expansions.[8]

A common problem encountered with PC systems used in precast components is excessive creep deformation under service conditions. Creep takes place in PC as the result of molecular movement in the viscoelastic resin binder. A typical creep compliance (or strain per uniaxial unit sustained stress) and Poisson's ratio versus time for PC is shown in Fig. 8. A stress intensity ratio of 20% was chosen to avoid complications resulting from nonlinear viscoelastic behavior and because PC is usually designed with a high safety factor. The application of larger load levels would also have been more difficult because of the high strength of PC.[9] Previous creep studies with PC determined that excessive creep deformation and catastrophic failure often occur when the creep stress intensity ratio exceeds about 50%.[10] More than 20% of the final creep for PC takes place within one day and more than 90% of the final creep occurs within six days. The specific creep (which is the creep strain divided by the sustained stress) is 28 $\mu\varepsilon$ MPa^{-1} after 95 days, which is comparable to what was observed with other PC systems using virgin resin.[11] The PC creep strain is higher than the one corresponding to Portland cement concrete. It should be noted, however, that different conditions affect the creep behavior of polymer composites and Portland cement-based materials. The creep behavior of polymer composites is sensitive to temperature variations while the creep behavior of Portland cement-based materials is sensitive to humidity changes. It is also noted in Fig. 8 that the Poisson's ratio of PC, measured during the compressive creep stress, increases by about 25% during the three month test period. This time dependency of the PC Poisson's ratio needs to be taken into consideration in the analysis of structural elements.

CONCLUSIONS

The time and temperature dependent properties fo PC using an unsaturated polyester based on recycled PET were investigated. Test results revealed that the material can achieve more than 80% of its final strength in one day, an important advantage in many construction and structural applications. The material experiences a loss in strength at high temperatures, which may be important if the PC is used in precast building panels, for example. However, depsite this loss in strength at high temperatures, the material remains strong when compared to Portland cement concrete. Special precautions should be taken in cases involving large sustained loads and/ or high temperatures because the viscoelastic nature of the resin binder can result in unreasonably high deformations. Special resin formulations, adequate supports and/or large safety factors would be advisable in these instances. Field applications and continuous monitoring of PC using unsaturated polyester resins based on recycled PET would really determine the long term behavior of the material under field conditions.

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