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# Fibre-reinforced geopolymer concrete with ambient curing for in situ applications

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**Abstract** Geopolymer concrete is proven to have excellent engineering properties with a reduced carbon footprint. It not only reduces the greenhouse gas emissions (compared to Portland cement-based concrete) but also utilises a large amount of industrial waste materials such as fly ash and slag. Due to these positive attributes, it is becoming an increasingly popular construction material. Previous studies on geopolymer concrete report that heat curing plays an important role in gaining higher compressive strength values (as opposed to ambient curing), and hence the application of this material could be limited to precast members. Therefore, this research was aimed at investigating the effect of heat curing by comparing the mechanical properties such as compressive strength and ductility of ambient cured and heat cured geopolymer concrete samples. It is worth noting that there was marginal strength change due to heat curing. In Australia, fibre-reinforced geopolymer concrete is being used in precast panels in underground constructions. Commercially available geopolymer cement and synthetic fibres are effectively being used to produce elements that are more durable than what is currently used in industry. As a result, this research investigated the effects of polypropylene fibres in geopolymer concrete using 0.05 and 0.15 % fibres (by weight). The addition of polypropylene fibres enhances the compressive strength and the ductility of geopolymer concrete.

## Introduction

At the moment, there is overwhelming scientific consensus to prove that climate change is happening. Climate change due to global warming is one of the biggest social, political, economical and environmental issues that will have far reaching effect on all living organisms on this planet. Global warming is caused by the emission of greenhouse gases such as carbon dioxide, methane and nitrous oxide into the atmosphere. It is reported that the production of cement contributes about 5–7 % of $CO_2$ emissions globally [1]. Production of one ton of Ordinary Portland Cement (OPC) releases approximately one ton of $CO_2$ into the atmosphere [2, 3]. Nevertheless, the overall use of concrete is second only to the use of water around the world [2]. It is reported that world cement consumption for 2011 was 3.7 billion metric tons and it is expected to remain around 4 % growth from 2014 to 2016 [4]. Research into geopolymer concrete (an alternative to OPC concrete) started decades ago, and currently this greener construction material is in commercial use. Davidovits [5] suggested that an alkaline solution could be used to react with silicon and aluminium of a material and to produce binders similar to cement binder. Since this chemical reaction is a polymerisation process, Davidovits [5] named this new binder as 'geopolymer'. The source materials used to produce geopolymer concrete mainly comes from industrial waste materials such as fly ash, granulated blast-furnace slag and rice husk. A recent research [6] shows that there is a possibility of

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using industrial effluent as a partial replacement for commercially available alkaline solutions.

Hardjito et al. [7] reported that curing temperature plays an important role in the geopolymerisation process of fly ash-based geopolymer mortar. They concluded that higher curing temperatures result in a faster rate of time for the geopolymerisation process to occur. It is reported that longer curing times result in higher compressive strengths in geopolymer concrete, because it improves the geopolymerisation process [8]. There was an increase in compressive strength with the increase in curing temperature from 60 to 70 °C. However, curing temperatures greater than 70 °C actually lowered the compressive strength of the geopolymer concrete samples.

Industry has not yet fully embraced geopolymer concrete. This is mainly because the information pertaining to the service life and the durability of geopolymer concrete applications or infrastructure has yet to be quantified. Another factor is the high degree of variability in relation to environmental and financial costs of geopolymer concrete. The cost of geopolymer concrete is dependent of the material source location, the energy source and modes of transport [1]. Depending on these three variables geopolymer concrete may be more or less expensive than OPC concrete. Australia has an abundance of fly ash that is produced from coal-fired power stations that are located throughout the country. The development of a recommended practice handbook on geopolymer concrete by the Concrete Institute of Australia in 2011 would provide further guidance and foster a better understanding of this material in construction to industry.

## Fibre-reinforced concrete

Geopolymer concrete has highly desirable structural engineering properties, which can lead to significant environmental and economic benefits. Its use is, however, limited by concerns regarding an increased brittleness compared to OPC concrete [9]. Neville and Brooks [10] suggested that cementitious materials are generally brittle in behaviour and are inherently weak in resisting tensile forces. Low amounts of tensile force can cause a sudden failure which is usually caused by the proliferation of cracks. Steel reinforcement is a common method of reinforcing the tensile strength of cementitious materials. The addition of fibres to cementitious materials works on a similar theory whereby fibres act to transmit tensile forces across a crack. Fibres in general and polypropylene (PP) fibres in particular have gained popularity in recent years for use in concrete, mainly owing to their low price and excellent characteristics, but also because they reduce the shrinkage and improve cracking resistance and toughness of plain concrete [11]. The idea of reinforcing materials is not new and can be dated back to the time of the ancient Egyptians where masonry works were undertaken with mud and straw.

Fibres used to reinforce concrete can be placed into two categories [12]: low modulus, high elongation fibres such as nylon, polypropylene and polyethylene in which the fibres primarily enhance the energy absorption characteristics and high strength, high modulus fibres such as steel, glass and asbestos in which the fibres enhance the strength, as well as the toughness of the composites. Karahan et al. [11] concluded that PP fibres have unfavourable effects on flexural tensile strength at the volume fractions used in their study (0.45, 0.9 and 1.8 kg/m$^3$). Fibre-reinforced concrete has a flexural tensile strength that is slightly smaller than concrete without fibres, and it decreased as the fibre content increased [11].

It was found that adding polypropylene fibres actually causes a small decline in the fracture energy and fracture toughness of concrete [13]. The fibre concretes generally gave small reductions in the compressive strength, which were of the order of 4 ± 8 % in the case of concretes with 0.15 % fibres. It should be noted that the polypropylene fibres are effective in controlling the post-cracking behaviour and preventing unforeseen failure as witnessed for plain concrete. Karahan et al. [11] observed that polypropylene fibres reduced the workability and unit weight of fly ash concrete and did not show a significant effect on the compressive strength and modulus of elasticity of fly ash concrete. Fly ash in concrete (either separately or together) reduces drying shrinkage. The lowest drying shrinkage of fibrous concrete with fly ash occurs when polypropylene fibres and fly ash are present. PP fibre-reinforced concrete had marginally more resistance to freeze–thaw when compared to concrete without fibres. The inclusion of fly ash in OPC concrete has a more significant effect on the resistance to freeze–thaw compared to concrete with polypropylene fibres.

## Geopolymer concrete with fibres

Wimpenny et al. [14] conducted a 3-year study to develop fibre-reinforced geopolymer concrete products for underground infrastructure. In particular, they investigated the durability, workability and strength of fresh and hardened fibre-reinforced geopolymer concrete. The characteristics listed above of fibre-reinforced geopolymer concrete were compared to a control mix of Portland cement-based concrete and 40 kg/m$^3$ of steel fibres. An acceptable level of workability was produced with geopolymer concrete and 8 kg/m$^3$ of synthetic fibre. Fibre-reinforced geopolymer concrete was found to outperform the control mix with

**Table 1** Details of the batches

| | Curing method | | PP fibres (% by weight) |
|---|---|---|---|
| | Oven curing at 80 °C (h) | Ambient curing (h) | |
| Batch 1 | | 24 | 0.15 |
| Batch 2 | | 24 | 0 |
| Batch 3 | 3 | | 0 |
| Batch 4 | | 24 | 0.05 |
| Batch 5 | 6 | | 0 |

**Table 2** Chemical constituent: percentages

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ |
|---|---|---|---|---|---|---|---|
| 51.8 | 24.4 | 9.62 | 4.37 | 1.5 | 0.34 | 1.41 | 0.26 |

**Table 3** Mix proportions

| Material | Quantity (kg/m$^3$) |
|---|---|
| Alkaline liquid/fly ash | 0.45 |
| Fly ash | 381 |
| Sodium hydroxide solution (8 M) | 49 |
| Sodium silicate (Grade D) | 122 |
| Fine aggregate | 554 |
| Coarse aggregate | |
| 7.5 mm | 647 |
| 10 mm | 647 |

regard to flexural strength, durability and shrinkage whilst reducing carbon emissions by approximately 70 %.

Most of the reported literature discussed the mechanical properties and durability of fibre-reinforced geopolymer concrete, and the necessity of heat curing limits the application of this material to precast elements. This research paper investigates the effect of PP fibres, heat curing and ambient curing on the compressive strength and ductility of geopolymer concrete. One of the aims of this project is to investigate whether ambient curing can be used instead of heat curing so that the application of geopolymer concrete can be broadened to in situ applications.

## Experimental programme

An experimental programme was designed to prepare and test geopolymer concrete. There were two test variables namely the amount of PP fibres used and the curing method/duration. Three levels of PP fibres (0, 0.05 and 0.15 % by weight) and three levels of curing (ambient cured for 24 h, oven cured for 3 and 6 h) were investigated. Tests were performed in duplicate for each level of PP fibre amount and each level of curing. The main experimental programme consisted of compression testing of five batches of geopolymer concrete samples on 7, 14, 21, 28 and 50 days. Table 1 gives the details of each batch. All together fifty specimens were tested for unconfined compressive strength in this experimental programme.

## Materials

The majority of the geopolymer studies conducted in Australia is based on low-calcium fly ash, whilst international researchers have investigated the material made with high-calcium fly ash [15, 16]. However, it is documented that low-calcium fly ash is preferred because of the fast setting time associated with the high-calcium fly ash [17].

Fly ash used in this investigation was Type F (low calcium) fly ash of approximately 15 µm particle size and was sourced from Pozzolanic Millmerran. The chemical composition of the fly ash is given in Table 2. The density of fly ash was found to be 1100 kg/m$^3$.

Fine dry sand used in the investigation had a bulk density of 1494 kg/m$^3$, water absorption of 8 % and particle size smaller than 425 µm. Two different sizes of coarse aggregates were used in this mix (7.5 and 10 mm nominal aggregate size).

Alkali activators used to make the geopolymer concrete included a solution of Sodium silicate and Sodium hydroxide. Sodium silicate solution is available in different grades. For this study, Grade D Sodium silicate solution with a modulus ratio ($M_s$) of 2 ($M_s = SiO_2/Na_2O$ and $Na_2O = 14.7$ % and $SiO_2 = 29.4$ % and solids = 44.9 % by mass), and specific gravity of 1.5 was utilised. The Sodium hydroxide used in this study was in a solid pellet form (90 % pure). It was dissolved in water to create 8-molar sodium hydroxide solution.

## Mix design

The mix design used in this research was based on the work reported by Zhao and Sanjayan [18] and is shown in Table 3.

Aggregate weights shown in Table 3 are in the saturated surface dry condition. The same mix design was used for all the samples in this research project with the only variations occurring for the curing regime and the percentage of fibres added.

## Sample preparation

One day before each batch of geopolymer concrete samples (200 mm high × 100 mm diameter) was made, and there were several steps undertaken as part of the preparation work required. As Sodium Hydroxide pellets were utilised, it was necessary to dilute it with water to achieve the required molarity of 8 M. The required amount of water and Sodium Hydroxide pellets were measured. The water was placed into a plastic bucket, and Sodium Hydroxide pellets were gradually added and stirred. The addition of the Sodium Hydroxide pellets to the water caused heat to be generated as an exothermic reaction occurred. Once the Sodium Hydroxide pellets had totally dissolved in the water, the required amount of sodium silicate solution was added, and the liquid solution was mixed. The top of the bucket that housed the Sodium Hydroxide solution was then covered with plastic wrap to minimise the chance of any contamination or evaporation. All the required amounts of aggregate (7.5 and 10 mm) were measured as per the mix designs listed in Table 3. Aggregates were brought to the saturated surface dry (SSD) condition so that they neither absorbed the chemical solutions nor contributed more water to the mix.

The following steps were adhered to on the day of mixing. Sand, fly ash, 7 and 10 mm aggregates were added to the portable concrete mixer and mixed for 1 min. If the batch includes PP fibres, then they were added in with the other dry ingredients. Sodium silicate solution that was prepared the day before was slowly added to the mix. This ‘wet’ mixing occurred for 4–5 min. A sheet of plastic was used to cover the portable concrete mixer to stop the loss of any material (particularly fly ash as it is not a dense material). Each batch of geopolymer concrete was then casted into steel cylindrical moulds. The fresh geopolymer concrete was stiff until compacted using a vibrating table.

Once the geopolymer concrete was placed into the moulds, a plastic wrap was placed over the moulds to stop any evaporation in the ambient and oven-cured samples. As discussed in the experimental programme, there were three curing regimes implemented: ambient curing in the workshop for 24 h and oven curing for 3 and 6 h at 80 °C temperature. The geopolymer concrete samples were then removed from their moulds after their respective curing regime was complete and placed in a room that provided a consistent climate (23 °C and 50 % humidity) until the time of testing.

## Testing

All samples were tested until failure in a 2000 kN capacity SANS hydraulic compression testing machine (Fig. 1) in accordance with AS 1012.9 [19]. A loading rate of 2 mm/min was used for compressive testing, which allowed the specimen to deform under loading without a dynamic loading effect. Two strain gauges of a 90-mm gauge length were placed longitudinally at the middle third in two diametrically opposite sides. All the specimens were prepared using this method. The specimens thus prepared were tested (Fig. 1) and the axial load and the platen to platen displacements together with the data from strain gauges using system 5000 were recorded.

**Fig. 1** Experimental set up

## Results and discussion

Figure 2 shows the tested samples with and without fibres. When the failure patterns are analysed, it can be seen that the cracks passed through the mortar and fibres for most of the samples. Recorded data were analysed for the load and axial deformation.

## Compressive strength

Figure 3 displays the effect of curing on compressive strength development (Batch 3 compared to Batch 2). Oven-cured samples (Batch 3) provided higher initial (7 days) compressive strength than ambient cured samples (Batch 2). However, the curing method had no significant effect on compressive strength values after 7 days, as the ambient cured samples of Batch 2 were consistently stronger in compression than the other batches.

Figure 4 displays the effect of oven-curing time on compressive strength development (Batch 3 compared to Batch 5). Batch 5 consistently outperformed Batch 3 in regard to compressive strength values collated over the entirety of the testing regime of each batch. Compressive strength development was minor for Batch 5 over its 35-day testing programme. This phenomenon is supported by Recommended Practice. Geopolymer Concrete [20],

**Fig. 2** Tested samples

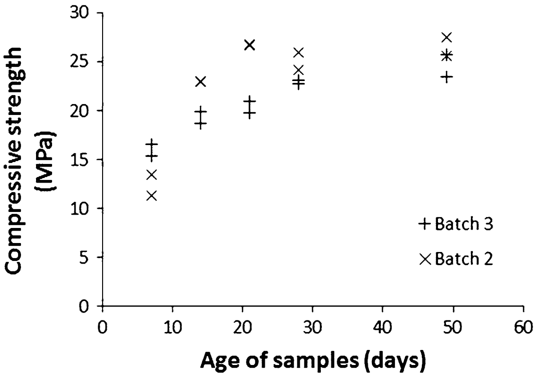

**Fig. 3** Effect of curing on compressive strength development

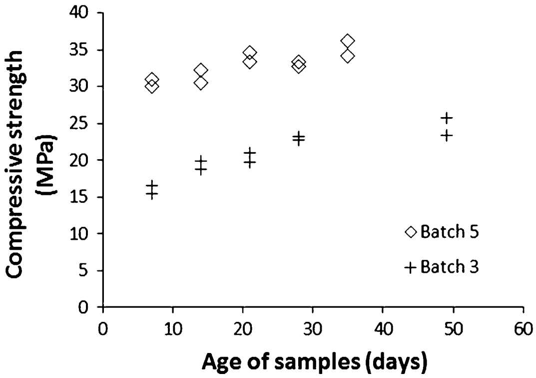

**Fig. 4** Effect of duration of curing on compressive strength (oven-cured samples)

which also found that 80–90 % of the final compressive strength of geopolymer concrete, can be attained over a short period of time if samples are left to oven cure for a significant period of time at temperatures ranging between 80 and 90 °C. Vijai et al. [21] found that the compressive strength development of geopolymer concrete occurred quite rapidly when oven curing was implemented, whilst it took 28 days to achieve a value close to the ultimate compressive strength if ambient curing was used. Overall, this trend occurred for geopolymer concrete samples from the experimental programme in this research.

Ambient curing of geopolymer concrete does not show a considerable difference in the compressive strength compared to heat curing at 28 days. However, ambient curing resulted in developing low-strength geopolymer concrete. Further work is required to refine the mix design used in this study in order to improve the compressive strength values achieved. Recent research conducted by the authors demonstrated that compressive strength can be improved by replacing some fly ash in the mix design by ground-granulated blast-furnace slag.

Reported literature mainly discussed oven curing for geopolymer concrete. Whilst oven-cured samples achieved a greater compressive strength over the first 7 days, curing samples under ambient conditions appear to be a viable alternative. Therefore, this research suggests that ambient cured geopolymer concrete can potentially broaden its use in cast in situ applications.

Hardjito et al. [7] found the stress–strain curves developed for fly ash-based geopolymer concrete portrayed a high level of a similarity to a model developed by Collins et al. [22] for OPC concrete. A bell curve best describes the shape of the curve for OPC concrete, which would result in a material that is reasonably ductile. When analysing the stress–strain curves of the geopolymer concrete samples prepared in the experimental programme, it can be found

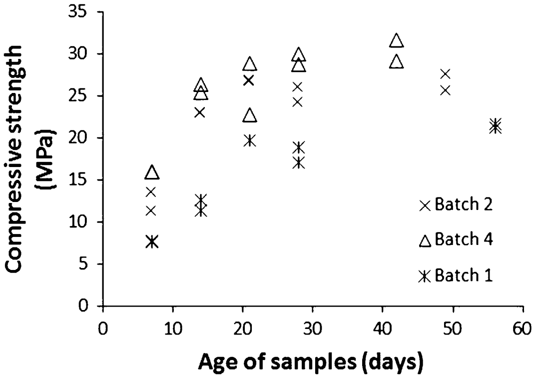

**Fig. 5** Effect of polypropylene fibres on compressive strength

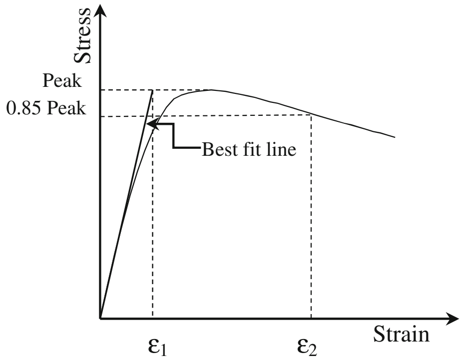

**Fig. 6** Ductility factor measurement

that the majority of the curves has a steep descending branch with an overall bell shape.

Figure 5 shows the effect of PP fibres on compressive strength development (Batch 2 compared to Batches 1 and 4). Batch 4 with 0.05 % fibres displayed the greatest compressive strength values over all testing days. However, Batch 2 (which had no PP fibres) outperformed the samples from Batch 1(0.15 % PP added by weight of the mix). It is possible that an optimum amount of PP fibres (added by weight) to the geopolymer mix may exist, as the batch with more PP fibres (Batch 1) had significantly smaller compressive strength values recorded over the entirety of its testing regime. Whilst the addition of PP fibres increased the compressive strengths (Batch 4 compared to Batch 2), it also provides a greater resistance to cracking (Fig. 2). A geopolymer concrete sample without PP fibres generally has cracks that propagate from the centre of the top of the sample and travel in a 45° angle towards the sides of the sample. This area of failure is similar to an upside down 'V'. Samples with PP fibres limit the propagation of cracks and never fail in an identical way due to the random distribution of the PP fibres.

## Ductility

Although ductility is an essential characteristic of a well-designed structure, there is no consensus on the best method of measuring ductility. Displacement ductility factor, energy dissipation and stiffness are some parameters used to evaluate column performance. In column analysis, the most widely accepted definition of displacement ductility factor is the ratio of ultimate displacement of the column and the displacement of the column at first yield of axial reinforcement. Consensus on the definition of ultimate displacement has not been achieved and varies depending on the researcher. Ahn and Shin [23] and Paultre et al. [24] defined it as the displacement corresponding to 80 % of the peak load along the descending branch of the load versus displacement curve, whilst Rui et al. [25] defined the same using 85 % of the peak load. Instead of displacement of the column at first yield of axial reinforcement, Woods et al. [26] used the displacement corresponding to peak load. Although unconventional, they argue that the displacement corresponding to peak load is known with greater accuracy. Displacement ductility factor ($\mu$) defined below is used to analyse the performance of the samples tested in this research.

$$\mu = \frac{\varepsilon_2}{\varepsilon_1} \tag{1}$$

where $\varepsilon_1$ is related to the approximate limit of elastic behaviour and $\varepsilon_2$ is the strain corresponding to 0.85 of the peak stress in the descending branch. These terms are clearly defined in Fig. 6.

The best fit line shown in Fig. 6 is obtained by the linear regression analysis for the linear part of the stress–strain curve for each specimen. This line is then extrapolated to intersect the peak stress of each specimen. This definition is an indication of the softening slope of the stress–strain curve. It has been used to find the ductility of concrete columns previously and recently to obtain the ductility of geopolymer concrete mortar [27]. The ductility factor comparisons for geopolymer concrete thus calculated are shown in Figs. 7 and 8.

When batches 2 (ambient curing), 3 (3 h at 80 °C) and 5 (6 h at 80 °C) are compared in Figs. 4 and 5, it can be seen that initial strength gain increases for these batches in respective order. On the contrary, batches 2, 3 and 5 have a decreasing trend in the ductility factors in respective order. This means that geopolymer concrete with lower initial strength shows greater ductility. Geopolymer concrete with higher initial strength has a narrower shape in the stress–strain curve. The same phenomena were reported for geopolymer mortar in the past [27].

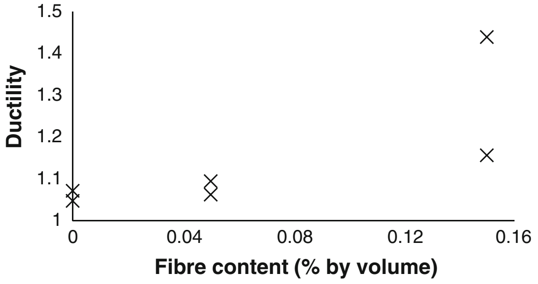

**Fig. 7** Variation of ductility factor with fibre content

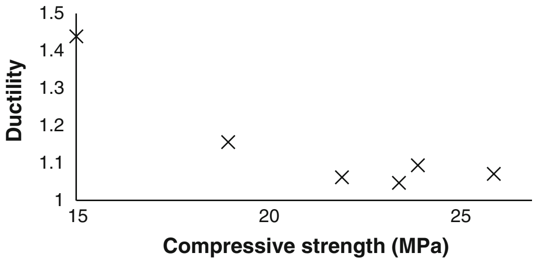

**Fig. 8** Variation of ductility factor with compressive strength

Samples with PP fibres incorporated into the mix possessed greater levels of ductility than samples with no fibres in them (Fig. 7). Post-peak behaviour of the stress–strain curve is affected by the inclusion of fibres. Fibres provide a resistance for the crack propagation and this converting the brittle behaviour to a ductile behaviour. A similar behaviour was observed for PP fibre-reinforced OPC concrete in the past.

Foster et al. [28] stated that the greater the compressive strength of OPC concrete is, the more the brittle it is. This trend conforms to what has occurred for the geopolymer concrete samples in the experimental programme (Fig. 8) in this study.

Ductility measurement for geopolymer concrete has never been discussed in the past. Although higher initial strengths can be gained by heat curing, this marginally reduces the ductility of the material. Therefore, ambient curing for geopolymer concrete is further supported by the ductility measurements reported in this paper. Addition of PP fibres improves the ductility as they retard the crack propagation.

## Conclusions

This paper investigated the characteristics (such as compressive strength and ductility) used to define the behaviour of fly ash-based geopolymer concrete. By preparing five batches of geopolymer concrete in the experimental programme, it was possible to determine the effects of curing method and polypropylene fibres on geopolymer concrete.

The compressive strength of geopolymer concrete is not affected by the curing method for low-strength concrete, and the majority of the strength of geopolymer concrete is reached in 21–28 days. Therefore, there is a great potential for geopolymer concrete to be cast in situ.

Overall, the addition of polypropylene fibres improved the compressive strength and ductility of geopolymer concrete.

Further research is needed to investigate the effect of fibres on flexural strength of geopolymer concrete. Recent research by the authors has shown that replacing a portion of fly ash in the mix design with ground-granulated blast-furnace slag will produce high-strength geopolymer concrete.

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