Modern materials for underground support*

by M. McChesney†

SYNOPSIS

The properties required of a support material for underground tunnels are discussed and, because concrete is both economical and easy to apply, a number of new reinforcing materials for concrete are examined with particular reference to these properties. From about thirty tests on different types of reinforced concrete, it is concluded that the addition of polymer to a concrete does not seem to influence the concrete's post-failure behaviour, and the only benefit to be achieved by this addition is to increase its flexibility (or to decrease it, depending on the polymer). Steel fibres tend to increase both the strength and stiffness of the concrete, but polypropylene fibres, although having definite load-carrying capacities, provide non-stable failure, also known as brittle failure. The best result was obtained for concrete reinforced with steel wire: the post-cracking strength was very good and was maintained for a considerable deformation.

SAMEVATTING

Die eienskappe wat van 'n stutmateriaal vir ondergrondse tonnels verlang word, word bespreek en omdat beton nie alleen ekonomies is nie, maar ook maklik om te gebruik, word 'n aantal nuwe wapeningmateriale vir beton ondersoek met spesiale verwysing na hierdie eienskappe. Uit ongeveer dertig toetse met verskillende soorte gewapende beton word die gevolgtrekking gemaak dat die byvoeging van 'n polimeer by 'n beton blykbaar nie die beton se gedrag na faling beinvloed nie en die enigste voordeel wat deur hierdie byvoeging verkry kan word, is 'n verhoging van sy buigsaamheid (of 'n vermindering daarvan, afhangende van die polimeer). Staalvesels is geneig om sowel die sterkte as die styfheid van die beton te verhoog, maar hoewel hulle definitiewe dra-eienskappe het, gee polipropileenvesels aanleiding tot nie-stabiele faling, ook bekend as brosbreuk. Die beste resultaat is verkry met beton wat met staaldraad gewapen is: die sterkte na kraking was baie goed en is vir 'n aansienlike vervorming gehandhaaf.

Introduction

During its excavation and operating life, a tunnel can undergo major changes in stress and, once this stress becomes higher than the strength of the rock, fracturing and slabbing occur. Ideally, the shape of the excavation should be such as to minimize the concentrating effects of stress. However, this is seldom possible, and the stresses encountered as a result of depth rule out the prevention of rock fracture.

A common problem is that of jointed or blocky ground. Laminated rock produces an infinite number of weak bedding planes and, when an excavation is made, nothing prevents the falling away of small localized pieces of ground. Once this happens, the coherence of the entire rock mass becomes less, and more and more pieces are dislodged.

Rock in the conditions described requires to be supported, and the most effective support is one that brings out the self-supporting characteristics of the rock. Both active and passive support can be used, the active being more effective if it is possible to install. However, where large stresses and large displacements occur, yielding support is required. This allows the rock mass to shift but, at the same time, keeps it coherent and to a large degree self-supporting.

Objectives

Various forms of yielding support are used in practice, and a number of new materials are being tried. Two main properties are desirable in such supporting material: low flexural stiffness and good ultimate strength.

The first of these requires that the material should not have a high elastic modulus, i.e., that a large failure strain is developed for a given load. If a low elastic modulus is required, it is at the expense of strength.

The second implies that the material should exhibit good load-bearing capacity after failure. This characteristic is usually obtained by a composite material that has been reinforced. Reinforcing wire, glass fibres, and steel fibres are some of the possible reinforcing materials.

Although these properties are both desirable, they are seldom found together in an economically possible material. This is because fibres, which increase the ultimate strength, inhibit micro-cracking, and this in turn stiffens the material.

Another necessary engineering criterion of design is that of ductility at full load capacity, the effect being to provide stable failure.

Other important requirements of a supporting material are, of course, economy and workability.

The aim of this paper is to explore the use of modern materials, and to highlight their advantages and disadvantages. It must be emphasized that the applicability of modern materials is extremely limited owing to a number of problems that arise. These include properties such as creep, handling, cost, heat- and fire-resistance. Nevertheless, once the properties of a supporting material have been clearly defined, some effort can be made to find a suitable material.

Reinforced Concrete

Although conventional steel-reinforced concrete is not new, it is discussed here briefly so that comparisons can be made.

Concrete is cheap and its constituents are always available; it has the capacity to develop high compressive strength, durability, and fire-resistance. It becomes much more effective when reinforced with steel or when it is prestressed. In spite of all these commendable

*This paper is an abridged version of a dissertation that won one of the Institute's student awards for 1975.

†At the time of writing, final-year student in B.Sc. (Mining Engineering), University of the Witwatersrand, Johannesburg.

qualities, its poor flexural strength, low tensile cracking strain, limited ductility, and limited ability to absorb energy have posed many problems[1]. Probably the most significant weakness of concrete is its low failure strain. This leads to progressive cracking and spalling, which makes the material highly permeable, less durable, and less sensitive to the external effects that can cause corrosion of the steel reinforcement.

Shotcrete reinforced with wire mesh has characteristics very similar to those of reinforced concrete, but it has been established that it is moderately more flexible. Its modulus of elasticity, failure strain, and flexural strength vary widely depending on the design of the mix, the application, and the environmental conditions.

Steel Fibre Reinforced Concrete[2]

Some problems have been encountered with the mixing and compaction of steel fibres in concrete, and it has been claimed that fibres increase the entrapment of air in the matrix, although this has been disproved[3]. The modulus of elasticity increases only marginally over that of conventional reinforced concrete and appears to be about 5 per cent. The increase in tensile and compressive strength is also regarded as marginal, but the flexural strength is considerably better.

Its resistance to impact loading is probably this material's most useful quality, improvements of 400 per cent having been obtained. Differences in shrinkage and creep are not significant with up to 2 per cent by volume of steel fibres. The mode of failure is stable or non-brittle.

The cost of concrete reinforced with steel fibre is prohibitive; it is as much as five times more expensive than conventional reinforced concrete.

Glass Reinforced Concrete[4, 5]

Glass reinforced concrete, like steel fibre concrete, combines the tensile properties of the fibres with the compressive properties of concrete. The impact strength is again very good and the failure mode stable. The flexural strength is high — about 40 MPa — while the elastic modulus is much the same as it is for normal concrete (20 GPa). These figures apply to concrete containing a high percentage of fibre — 5 per cent by mass. It seems that higher percentages of fibre are possible, but, as the amount of glass fibre increases, so does the level of air entrainment. Therefore, 10 per cent is about the maximum fibre content and this obviously gives the best strengths.

This concrete has the added advantage that it is substantially lighter than other forms of concrete. At present, it is very expensive, although its constituents are readily available.

Propylene Reinforced Concrete[6]

Concrete reinforced with propylene fibres has properties that are similar to those of any fibre-reinforced concrete. Mixing and handling still present problems and, the longer the fibre length, the more difficult this becomes. Amounts of fibre of more than 1 per cent by mass are not generally possible. Coarse, fibrillated fibres are most effective; they are cheaper, and their bonding characteristic is better than that of polypropylene monofilaments.

As in most fibre-reinforced matrices, the impact resistance is very good. Flexural strength is increased, and good residual strength is obtained with stable failure. The load-bearing properties are not as good as those of steel-reinforced concrete. The flexural strength is about 6 MPa.

Polymer Concrete[7, 8]

The term *polymer concrete* is used loosely to describe the following.

Polymer Impregnated Concrete

Normal concrete is treated after it has hardened, and it becomes much stiffer and stronger. Polymer impregnated concrete is not suitable for use underground.

Polymer Cement Concrete

This concrete contains a monomer, and polymerization occurs after it has been placed.

Polymer or Resin Concrete

A monomer is combined with the aggregate, no cement being used.

Of these polymer concretes, the most suitable for use as a supporting material seems to be polymer cement concrete, a number of different polymer emulsions being available for addition to cement concretes. The most significant merit of polymer cement concrete is its increased flexibility Its elastic modulus is lower by about one-sixth, values of 10 GPa being not uncommon. This also increases the failure strain, and compressive strength is not affected. Good fire-resistant properties are maintained, and shrinkage and creep do not vary appreciably from those of cement concrete. It should be noted that polymer emulsions entrap air during the mixing, and the air content can become too high, resulting in a distinct drop in strength. Precautions should therefore be taken during mixing.

Resin concrete[9] is probably the most versatile of the modern materials, numerous systems being available, with a wide range of physical properties. Flexural strengths vary from 4 to 40 MPa (no fibre) with no shrinkage, and setting times are from 2 minutes to 1 week. Failure strains are large — 2 to 30 per cent.

Two main types of resin are used in polymer or resin concrete: epoxy[10, 11] and polyester resins. These exhibit different physical and chemical characteristics: epoxy does not shrink on curing whereas polyester does, and polyester is more acid and alkali resistant than epoxy. Both resins exhibit a very high creep rate, which increases with temperature. Heat- and fire-resistance is fairly good (owing to the high aggregate content), with a safe working limit of about 60 °C. Polyesters can produce toxic fumes, and skin contact should be avoided.

Resin compounds have been used successfully in Europe for tunnel support. Epoxy resins were diluted with rock flour (to a possible extent of 80 per cent), and the results were most satisfactory both from the engineering and the economic points of view.

Asbestos Reinforced Concrete

Very little is known about concrete reinforced with asbestos fibre, but some indication of the physical properties can be obtained from asbestos cement. Large amounts of asbestos are usually added (20 per cent), resulting in a stiff material with an elastic modulus of 30 GPa. A good flexural strength of 18 MPa is exhibited but with non-stable failure. Obviously, the fire resistance of this material is exceptional, but it is expensive and not very promising from an engineering point of view.

Experimental Work

A series of tests was conducted in the laboratory on beams of cement mortar containing various reinforcing materials. In addition, underground tests were carried out on longer beams made of shotcrete with and without reinforcing material. The specimen beams were not exactly comparable owing to the effects of aging and weathering on the concretes, but they could give reliable indications.

Materials

For the laboratory tests, a mortar was made to the following mix proportions:

Sand	276 kg	(6)
Portland cement	92 kg	(2)
Water	37 kg	(1).

It was cast in 51 by 102 by 500 mm beams:
c/w=2,2

Steel fibres	0,25 mm by 25 mm
Fibrillated polypropylene	3,2 mm by 51 mm
Steel wire	0,25 mm by 152 mm
Polymer	Natural polyisoprene plus silane.

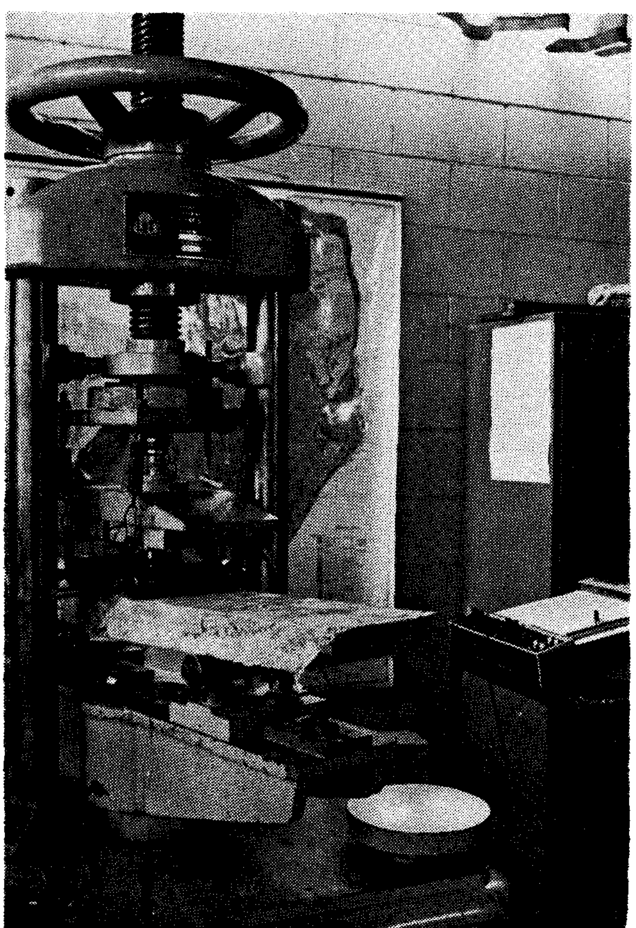

Fig. 1—The apparatus used in the tests

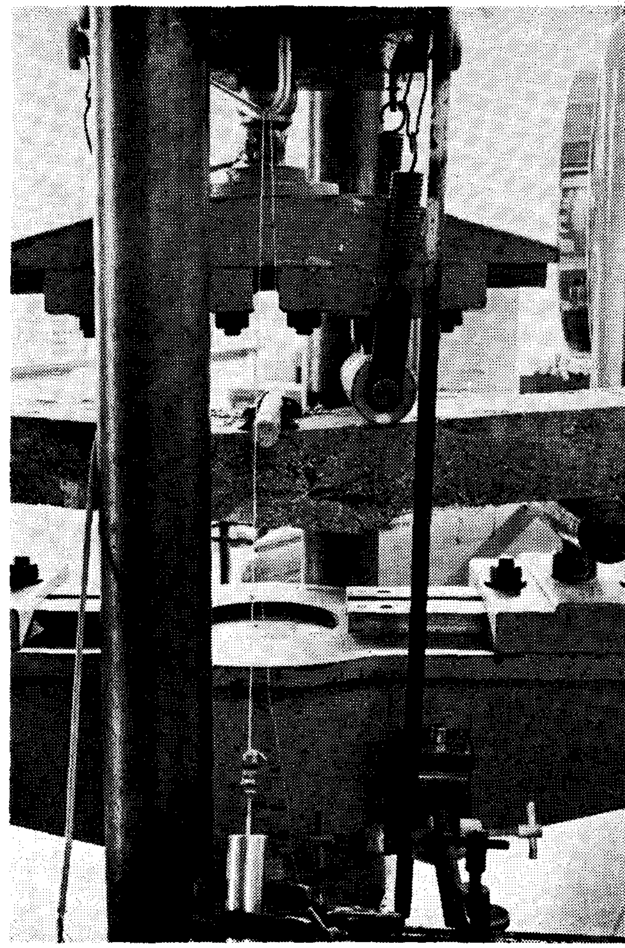

Fig. 2—The measuring equipment

For the field tests, shotcrete of the same mix proportions was sprayed into metal trays. When it had hardened, beams were cut out of the trays 52 by 152 by 500 mm:

Steel fibres	0,25 mm by 25 mm
Fibrillated polypropylene	3,2 mm by 51 mm
Polymer	Natural polyisoprene plus silane
Wire reinforcing	8 gauge
Wire-reinforced beam	Dimensions 52 mm by 152 mm by 1000 mm. Two longitudinal strands 140 mm long stirrups at 90 mm spacing.

Procedure

The testing procedure used was the modulus of rupture test or the four-point bending test. Beams were tested over a span of 406 mm on the apparatus shown in Figs. 1 and 2. The loading was measured by a calibrated load cell, and the deflection of the beam by a linear variable differential transformer. Deflections were measured on the top of each beam at its centre. These values are liable to some errors arising from the apparatus. Both

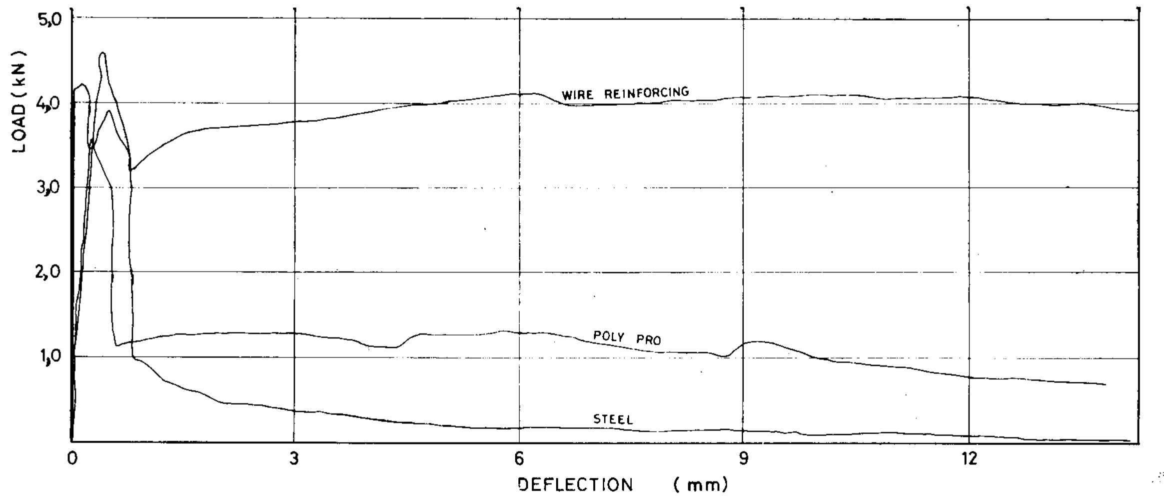

Fig. 3—Comparison between steel fibres (1 per cent), polypropylene fibres (2 per cent), and thick wire reinforcing, no polymer

the linear variable differential transformer and the load cell were connected to an X–Y recorder, which then plotted the load–deflection curves.

Results

An example of a load–deflection curve is given in Fig. 3.

From these curves, it is evident that the deflection measurements are not truly exact. Two possible reasons exist for this. The first is that the scale used on the deflection axis of the X–Y recorder was too large to record accurately the small deflections obtained in the elastic region. In some cases, the deflection was negligible and could not be read. However, the scale was set purposely to record large deflections and to illustrate the post-cracking characteristics. The second reason is that a certain amount of crushing of the beam occurred at the four loading points. In those cases, the load was applied but no deflection of the beam occurred. Therefore, the deflections measured were smaller than they should have been. This was a frequent cause of discrepancy, but its effect was nullified by the first-mentioned cause.

Although the resulting curves do not disclose any details of the elastic region, they do give an excellent indication of the post-cracking behaviour. This is the most important part for the materials tested, because they are all relatively stiff, except for the polymer-modified laboratory specimens.

Values for the flexural strength, σ, were obtained by use of simple bending theory and the following assumptions:

(i) The material was homogeneous.
(ii) The beam was originally straight and its section symmetrical about the plane of bending.
(iii) A plane section of the beam before bending remained plane after bending.
(iv) The value of Young's modulus was the same in compression and tension.

$$M=\frac{Fl}{6}$$

$$\frac{M}{I}=\frac{\sigma}{y}=\frac{E}{R}=\frac{Ed^2y}{dx^2}$$

$$\therefore \quad \sigma=\frac{My}{I}=\frac{M}{Z}$$

$$\therefore \quad \sigma=\frac{Fl}{bd^2} \qquad \text{(MPa).}$$

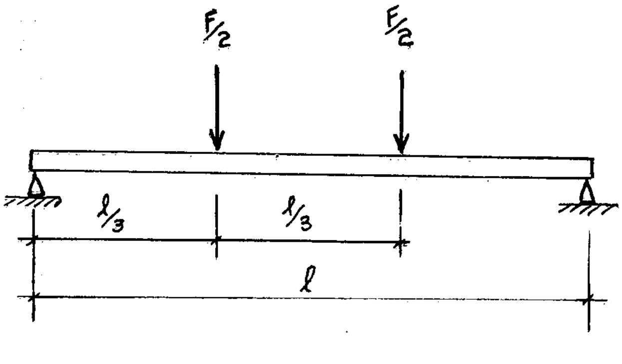

TABLE I

SOME EXPERIMENTAL RESULTS

Material	Flexural strength MPa	Modulus of elasticity GPa	Failure strain %
Laboratory Tests			
0,5 % steel, no polymer	6,66	24,9	0,027
1,0 % steel, no polymer	9,43		
2,0 % steel, no polymer	10,48		
2,0 % steel, 1,0 % polymer	8,26	14,1	0,059
2,0 % steel, 2,5 % polymer	6,24	7,0	0,089
2,0 % steel, 5,0 % polymer	5,36	2,5	0,214
2,0 % steel, 7,5 % polymer	4,21	1,4	0,301*
0,5 % polypropylene, no polymer	8,60		
1,0 % polypropylene, no polymer	6,59		
1,5 % polypropylene, no polymer	6,34		
2,0 % polypropylene, no polymer	6,20	24,7	0,025
1½ in wire, no polymer	7,08	18,4	0,038
6 in wire, no polymer	7,71		
Underground Tests			
Steel, no polymer	4,55		
Steel with polymer	4,64		
Polypropylene, no polymer	3,54		
Polypropylene, with polymer	3,63		
Wire reinforcing	4,18	28,9	0,014

*Secant modulus

By use of the same theory, a value can be obtained for the elastic modulus, E. It is assumed that E is equivalent to the average flexural modulus from the linear portion of the load–deflection curve:

$$E=\frac{5}{324}\frac{Fl^3}{dI}.$$

The values are given in Table I. Only the relevant E values were calculated.

Conclusion

The information obtained is valid only beyond the elastic limit, there being no conclusive result from which the elastic properties of the materials could be determined. However, it is clear that an increasing quantity of polymer lowers both the elastic modulus and the strength of a concrete.

The useful information obtained from the tests relates to the load-carrying capacity of a material after failure. The addition of polymer to a concrete does not seem to influence the concrete's post-failure behaviour, except for the shotcreted sample with polypropylene fibre, where the polymer had a marked effect. Therefore, the only merit of adding a polymer to concrete is to increase (or decrease, depending on the polymer used) its flexibility.

Steel fibres tend to increase both the strength and the stiffness of a concrete. Very good stable failure is obtained, with the load gradually falling off. The effect of reinforcing with steel wire ($1\frac{1}{2}$ in and 6 in long) is not good, resulting in brittle failure and no ultimate strength.

Polypropylene fibres have definite load-carrying capacities, but their failure is non-stable. More polypropylene increases this capacity but does not really affect the strength. Steel fibres have a more desired effect.

The most significant result obtained is that for the wire-reinforced sample. Its post-cracking strength is extremely high (shown by two tests) and is maintained for a considerable deformation. This far outstrips shotcrete reinforced with steel or polypropylene fibre.

Acknowledgement

The materials that were tested, together with the means of testing, were supplied by Rand Mines Limited. Their assistance is greatly appreciated.

References

1. Ortlepp, W. D. Failure of the concrete lining in an inclined shaft at great depth. *Advances in rock mechanics*. 1974.
2. Edginton, J., Hannant, D. J., and Williams, R. I. T. *Steel fibre reinforced concrete*. Building Research Establishment, 1974.
3. Ortlepp, W. D. A laboratory investigation into the flexibility of shotcrete and the effectiveness of various types of reinforcing mesh. ERPM, *Report no.* 1/72.
4. Allen, H. G., and Channer, R. S. Some mechanical properties of polymer modified portland cement sheets with and without glass-fibre reinforcement. *First International Congress on Polymer Concretes*, May 1975.
5. Pilkington Brothers Ltd. Some mechanical properties and behaviour patterns of CEM–FIL alkali resistant glass fibre/cement composites.
6. Shell Chemicals. *Polypropylene fibres in concrete*. Aug. 1968.
7. Browne, R. D., Adams, M., and French, E. L. Experience in the use of polymer concrete in the building and construction industry. *First International Congress on Polymer Concretes*, May 1975.
8. Swamy, R. N. Some engineering implications of design in polymer concrete. *First International Congress on Polymer Concretes*, May 1975.
9. Gebirgssicherung, G. M. B. H. *Basic features of the resin based compound support systzm*. May 1975.
10. Staynes, B. W. Epoxide resin as a structural material. *First International Congress on Polymer Concretes*, May 1975.
11. African Bitumen Emulsions (Pty) Ltd. *Epoxy resins and their use in the engineering field.*

Post-graduate studies

The Faculty of Engineering of the University of the Witwatersrand through its Graduate School of Engineering provides excellent opportunities and facilities for post-graduate studies in a wide range of fields. The Graduate Diploma in Engineering courses enable one to get up-to-date in specialist areas and also provide the possibility of obtaining the Master of Science in Engineering degree through course work and research. Candidates can also be admitted for the MSc (Eng) and PhD degrees by research only.

Write to the Secretary, Faculty of Engineering, University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg 2001, for further details and the booklet *Graduate Studies in Engineering* — 1977, or contact the Secretary in any of the appropriate departments of interest, e.g. Chemical, Civil, Electrical and Mining Engineering; the School of Mechanical Engineering; the Department of Metallurgy; and the Department of Mining Geology.

Applications for admission to coursework must be lodged not later than 31st January, and for coursework undertaken in the Department of Electrical Engineering not later than 31st December of the previous year.

Applications for admission for degrees received after 31st March will be considered with a view to admission from the commencement of the second term.