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Recycling of waste aggregate in cement bound mixtures for road pavement bases and sub-bases

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HIGHLIGHTS

- Cement bound mixtures (CBMs) with natural aggregate are used in road foundations.
- Six types of CBMs have been optimized, using five different waste materials.
- Physical–mechanical and leaching properties of the materials were investigated.
- Several tests have been carried out to characterize the mechanical performance.
- Not conventional CBMs give a relevant contribution to the bearing capacity.

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ABSTRACT

This paper discusses the results of a study aimed at designing cement bound mixtures for road construction, made with steel slag, ladle furnace slag, waste foundry sand, glass wastes and coal ash.

The mixtures were designed by means of Proctor, compression and indirect tensile tests. Their performance was investigated in terms of elastic modulus, through ultrasonic tests at different curing times. Satisfactory results were obtained, compression and indirect tensile strength at 7 days being up to 7.56 MPa and 0.78 MPa respectively, depending on the composition of the mixtures.

1. Introduction

The recycling of solid waste materials (SWM) in civil construction has been widely investigated in the last decades, as documented by several studies [1–19]. Among the different types of SWM, industrial by-products represent some of the most interesting for civil engineering applications [1–19].

Sas et al. [1] recently studied some chemical and physical–mechanical properties of steel slags used as material for a road subbase. From a chemical point of view, they stated that the steel slags can be used in pavement structures with no toxicological hazards, because the high contents of zinc and chromium measured are strongly associated with the slag internal microstructure. They reported satisfactory results in terms of California bearing ratio, as well as Young's modulus and resilient modulus, for some significant moisture contents and compaction conditions, with respect to the road subbase acceptance requisites. Manso et al. [2] verified the satisfactory durability of cement concretes made with electric arc furnace steel slags, with regard to the most severe environmental agents, ice and moisture. They also studied the toxicological potential, in terms of heavy metals, of both the steel slags and cement concretes. They found higher concentrations of toxic substances in the smaller particles of crushed steel slags, but also reported a cloistering effect of the cement concrete on the leaching behaviour, which therefore resulted as admissible within the regulations. Qiang et al. [3] analyzed the influence of ground basic

Abbreviations: UCS, unconfined compression strength; ITS, indirect tensile strength.

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oxygen furnace steel slags on both mechanical resistance and durability of cement concrete. They found that cement concrete with more than 30% of steel slag presented a lower compressive strength than a reference cement mixture without steel slag, at a water/cement ratio of 0.5. Reducing the water/cement ratio to 0.35, cement concrete with and without steel slag gave the same results. However, for low water/cement ratio, the steel slags had less influence on the drying shrinkage of the cement concrete, as well as on its permeability to chloride ions. The carbonation resistance of the cement concrete was also less affected by a high volume of steel slags at low water–cement ratio. Papayianni and Anastasiou [4] investigated the feasibility of recycling high contents of fly ash and ladle furnace slag as binders, and electric arc furnace slag as aggregates, for the production of cement concrete; their findings were very interesting, being characterized by high compressive strength, abrasion resistance and fracture toughness. Anastasiou et al. [5] investigated cement concretes made with fly ash as hydraulic binder instead of cement, recycled fine aggregates from construction and demolition wastes, as well as steel slag, instead of coarse conventional aggregates. They found that the use of the fine aggregates reduced strength and durability of the cement concrete and increased porosity. However, combining steel slag with the fine aggregates made it feasible to partially reduce the strength and durability loss. The substitution of 50% of cement with fly ash, along with a high volume of steel slag and fine aggregates, led to satisfactory results in terms of both strength and durability of the concrete. Etxeberria et al. [6] studied the mechanical behaviour of cement concretes made with two different types of foundry sand, electric arc furnace slags and blast furnace slag, as substitutes for raw sand and aggregates. They conducted slump tests, compressive and tensile tests, elastic modulus tests, verifying satisfactory results for the cement concrete made with the industrial by-products, in comparison with a conventional cement concrete. Ondova and Stevulova [7] evaluated the use of fly ash from coal combustion wastes, as partial substitute for cement in road cement concrete. Adequate compressive strength, as well as frost and chemical resistance, was achieved for the road cement concrete prepared using up to 15% of coal fly ash as binder. The authors also stated the environmental and economic advantages related to the recycling of coal fly ash. Guney et al. [8] conducted a laboratory study on soil-foundry sand mixtures, stabilized with cement and lime, for road subbase. Compressive strength, California bearing ratio, hydraulic conductivity, as well as leaching tests were done in order to verify the performance of the mixes. It was found that the mechanical behaviour was strictly related to the curing time, compaction energy, cement and lime contents. No hazardous leaching was found for the mixes with foundry sand investigated in the study.

Experiments on the use of foundry sand in controlled low-strength materials and concrete were conducted by Siddique et al. [9,10]. The results of leaching tests showed high concentrations of zinc, copper and lead, above the regulatory thresholds, so demonstrating hazardous behaviour of the raw material, if used without any additive. Siddique et al. [11] replaced natural sand, up to 20% by weight, in the production of cement concrete, studying its compressive and tensile strength at different curing times, as well as elastic modulus and ultrasonic pulse velocity. The results were quite satisfactory, with some improvement in the mechanical strength and durability of cement concrete containing the foundry sand. Topçu and Canbaz [12] used glass waste, up to 60% by weight, as coarse aggregate for cement concrete. It was verified that glass waste did not significantly affect the workability of the concrete, but it led to a limited, but not negligible, reduction in strength. The alkali–silica reaction (ASR), i.e. the chemical reaction that develops between the silica-rich glass grains and the alkali in the pore solution of concrete, was also considered. Meyer et al. [13] thoroughly discussed the ASR, which causes cracks upon expansion, weakens the concrete and shortens its life. They defined a number of measures to reduce the damaging effects of ASR: the use of glass wastes as fine aggregate in cement concrete production appears to be promising and technically feasible. Gautam et al. [14] conducted laboratory tests to study the recycling of glass wastes as both coarse and fine aggregate for cement concrete. They found that the use of glass wastes for fine aggregate replacement, up to 20% by weight, led to an increase in the compressive strength after 28 days ageing, even if with marginal reductions in the mechanical resistance for further increments of the waste glass content. Ammash et al. [15] investigated the feasibility of glass wastes recycling, using the 0/5 mm fraction, dosed between 10% and 40% by weight, as a fine aggregate in cement concrete and mortar. When 20% of glass wastes were used, the compressive strength at 28 days ageing was very close to that of the reference concrete made with conventional aggregates. Marginal expansion phenomena were observed for mortars with more than 20% by weight of recycled aggregate. Shayan and Xu [16] outlined that the ASR problem in cement concrete made with waste glass was strictly related to the glass content and its particle size. They found a satisfactory compressive strength of concretes made with large amounts of both coarse and fine waste glass, when replacing 25% of cement with fly ash; indeed any pozzolanic material, such as fly ash, silica fume or ground furnace slag, allows an effective ASR-suppressant action to be achieved. The authors also successfully studied the replacement of fine glass powder used as pozzolanic material, at up to 30% of the cement content.

The above studies demonstrate that the recycling of specific industrial wastes, mostly considered individually, in cement concrete for civil engineering constructions, has been widely investigated. However, the known applications concern the use of single or paired by-products and not their extensive use. This paper describes the combined and simultaneous use of five different industrial by-products for the production of cement mixtures. The laboratory study was conducted in order to verify the feasibility of simultaneously recycling different waste materials: steel slag, ladle slag, foundry sand, coal ash and glass wastes, in the aggregate structure of cement bound mixtures for road pavement foundations. The analysis investigated the five waste materials individually, plus their mixtures in six different proportions.

2. Materials and methods

2.1. Materials

Five types of waste materials, i.e. steel slag, ladle slag, foundry sand, glass wastes and coal ash, were used at various percentages in six different aggregate structures for cement bound mixtures to be used in road foundations. All the waste materials were provided by private Italian companies, located in the province of Padua (North-eastern Italy, Veneto Region), specialising in the recovery, valorisation and re-utilization of industrial by-products for road infrastructure.

The steel slags are a by-product of the steel industry based on electric arc furnaces (EAF). There are two types of EAF slags, from different suppliers, and named EAF B and EAF C. Ladle slag (LFS), also named "white slag", is the waste material that can be recovered in a ladle furnace for secondary metallurgy, after the casting process. Spent foundry sand (SFS) is a by-product of the steel and iron industry, usually characterized by a quite heterogeneous composition, recovered after the repeated use of high quality silica or lacustrine sand for the casting moulds necessary in the smelting processes of metallic or non-metallic products. The recycled glass wastes (RGW) come primarily from broken wine bottles, therefore coloured glass, which cannot be recycled by melting down for the production of new glass. Fly ash (CFA) is a fine dust, basically a by-product from the combustion of pulverized coal, which is transported from the combustion chamber by exhaust gases.

Portland cement CEM II/B LL 32.5R was used as hydraulic binder for all the cement bound mixtures in the investigation. The water used was transparent and without harmful contents of glucose, salts, acids, alkalis, other chemical or organic substances, as prescribed by the regulations.